

OHMIC HEATING *in* FOOD PROCESSING



Edited by

Hosahalli S. Ramaswamy • Michele Marcotte
Sudhir Sastry • Khalid Abdelrahim



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OHMIC HEATING *in* FOOD PROCESSING

Electro-Technologies for Food Processing Series

Series Editor

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Ohmic Heating in Food Processing, edited by Hosahalli S. Ramaswamy, Michele Marcotte, Sudhir Sastry, and Khalid Abdelrahim

Novel Food Processing : Effects on Rheological and Functional Properties, edited by Jasim Ahmed, Hosahalli S. Ramaswamy, Stefan Kasapis, and Joyce I. Boye

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Series Preface

Ohmic Heating in Food Processing edited by Hosahalli S. Ramaswamy, Michele Marcotte, Sudhir K. Sastry, and Khalid Abdelrahim is the second issue under the general umbrella of edited books in the Electro-Technologies for Food Processing Book Series involving the application of electro-technologies for various aspects of food processing, from pasteurization to sterilization, food preparation to food formulations, shelf-life extension to promoting food safety, food spoilage control to enhancing safety of foods, and from alternate to novel sources of the use of energy.

Electromagnetic technologies offer unlimited potential to processing applications in foods. Industrially, electro-technologies provide unique opportunities and advantages not necessarily found in other techniques. The book series will look at each of them in detail, especially from the point of view of various industrial food processing applications. Each book in this series is expected to be devoted to a specific area of electro-technology, covering all aspects of its science and engineering, chemistry and physics, biochemistry and nutrition, quality and safety, and development and technology, both basic and applied. Notable among the novel approaches in heating and food processing techniques are microwave and radio-frequency heating, electrical resistance or Ohmic heating, induction, and infrared heating applications. Use of pulsed electric fields, high-frequency magnetic fields, electric shockwaves, pulsed light, UV radiation, and ionizing irradiation offer potential nonthermal alternatives to food processing. On a different note, these also include such separation techniques as ultrasonics, electroacoustic dewatering techniques, electrodialysis, and ion-exchange systems. Stretching it further, one can look at other electromagnetic applications in spectroscopy, near infrared (NIR), Fourier transform infrared (FTIR), and nuclear magnetic resonance (NMR) techniques finding their way into analytical and imaging concepts. This book is special in that, rather than focusing entirely on one technology, it is focused on the rheology and functionality associated with all novel methods.

This volume, edited by leading scientists in the field, has an excellent collection of contributions from global experts focusing uniquely on the principles and applications of Ohmic heating as applied to foods. This volume has been designed to be a valuable tool to graduate students and researchers as a source of scientific information and is a useful addition to any library devoted to life sciences.

Look for the volume that will be devoted to Radio-Frequency Heating of Foods with editorial lead from Dr. George Awuah, thermal process manager, R&D Mars Petcare US, Franklin, Tennessee.

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Preface

This special volume is devoted to Ohmic heating of foods covering several aspects of its science and engineering, chemistry and physics, biochemistry and nutrition, quality and safety, development and technology, both basic and applied. The structure of this volume is uniquely different from other publications although covering most in a general sense to make them more interesting. The book tells readers how important the technology is and how to implement in practice. The book covers basic theory, principles, and applications of Ohmic heating technology and is divided into several sections with chapters addressing specific issues related to Ohmic heating. Each chapter provides a critical review of the state of knowledge of published research and combined with the personal experience of the authors. While addressing processing, the physical principles, chemical and microbiological basis of the process are dealt with. The impact of the technology on the quality and safety of food, novelty of the technology for food processing are also highlighted.

The book is designed primarily to be a valuable tool to graduate students and researchers as a source of information extending the contents of classical books on food processing while some chapters serve as standalone reference material. Each chapter is designed to be a valuable tool to food scientists and food technology professionals in the industry, wanting to follow new developments in food processing.

Section 1 covers the basics of Ohmic heating and is written by one of the world experts in the areas, Dr. Sudhir K. Sastry, from the Ohio State University. Chapter 1 gives an historic overview of the developments in Ohmic heating along with a brief review of present status and future outlook. It also details a number of reasons for continuing interest in Ohmic heating more than a century after its discovery. The second chapter emphasizes on the fundamental principles of Ohmic heating and the principal operational advantages and underlying constraints are discussed. This should help answer the question as to why Ohmic heating would be advantageous and should be considered for certain categories of products.

Section 2 is fully devoted to electrical conductivity which is one of the primary electrical properties responsible for Ohmic heating. Data on electrical conductivity are essential in designing a safe thermal processing procedure for food material processed by Ohmic heating. Chapter 3 highlights the importance of electrical conductivity with respect to Ohmic heating and the various methods that have been used for its measurement are detailed. Chapter 4 is devoted to gathering, compilation, and classification of available information on the electrical conductivity of the food materials. It provides very valuable data on electrical conductivity for the use of process designer. Discrepancies, agreements, and disagreements of the reported data are analyzed and reported. Chapter 5 deals with a detailed discussion on various factors that influence the electrical conductivity values, which included both product and system related variables. Chapter 6 is devoted to analyzing and modeling of all the electrical conductivity data in the context of Ohmic heating. Mathematical and empirical models have been developed by many researchers over the last two decades to predict the electrical conductivity of food materials as affected by influencing parameters. These models are generally validated and found to have good agreement for liquid and solid components used in real food formulation. Proposed models in the literature were classified based on the temperature dependency; voltage gradient and solid content of the products; and the existing models are presented in this chapter.

Section 3 of the book focusses on the biological effects of electricity (Ohmic heating) on various foods and food components. Chapter 7 describes Ohmic heating effects on microorganisms and enzymes, the two key parameters that are important with respect to the safety and stability of the product. Particular emphasis is given on the effects on microorganism and enzymes as related to the preservation and quality of foods. Chapter 8 deals with Ohmic heating effects

on food proteins and other biopolymers (carbohydrates and fats). These become important when products such as surimi are considered which are based on protein denaturation. Chapter 9 deals with electro-chemical reactions during Ohmic heating under moderate electric field processing. In electrochemistry, heat generation due to the passage of electric current is typically unwelcome and lead to problems. In food processing, however, this phenomenon is of great advantage and is often referred to as Ohmic heating.

Section 4 is devoted to the evaluation and characterization of Ohmic heating behavior and discusses Ohmic heating design parameters. Traditional processing methods used for conservation can seriously affect sensorial and nutritive values of processed foods. Emergent technologies like Ohmic heating can significantly improve quality meanwhile maintaining the safety levels. Ohmic heating provides a rapid and uniform heating, resulting in less thermal damage than a conventional heating. The operation allows manufacturers to obtain high-quality products with minimum sensorial, nutritional and structural changes, and processed foods can be produced in a short processing time. Chapter 10 describes the typical Ohmic heating behavior of foods. The electrode material used for Ohmic heating has attracted considerable attention. Due to the problems associated with stainless-steel electro-chemical reactions, generally titanium electrodes are employed in Ohmic heating systems. There has been considerable research exploring the use of stainless-steel electrodes under high-frequency AC heating in order to minimize the electrical interactions and electrode corrosion problems. Chapter 11 deals with these issues, common electrodes used and associated effects in Ohmic heating process. In Chapter 12, Ohmic heating of liquid food and solid–liquid suspension treatments are discussed with respect to energy efficiency and process control. The encountered difficulties and beneficial aspects (volume heating, fouling mechanisms, heterogeneous suspension treatment) are also reported.

Section 5 is devoted to issues in Ohmic heating equipment starting with small Ohmic heating equipment for lab applications in Chapter 13. Ohmic heater designs are discussed with respect to specific applications and are classified according to their application. Chapter 14 describes industrial tubular and fluid jet units for Ohmic heating. Technical aspects are discussed and various industrial applications are presented. The encountered difficulties and beneficial aspects are reported.

Section 6 deals with modeling issues related to Ohmic heating. In Chapter 15, a collinear Ohmic heater is modeled by solving simultaneously the equations of Laplace, Fourier, and Navier–Stokes. Chapter 16 compares modeling of static versus continuous flow Ohmic heating systems. Models to predict distributions of voltage, temperature, and velocity within the Ohmic heater are discussed including the effects of principal Ohmic heating variables on model predictions. Chapter 17 is devoted essentially to sensitivity analysis of Ohmic heating process. Process sensitivity analysis is one of important steps for a successful process development, since it can provide basic knowledge of how the variation in the output of the process can be apportioned, qualitatively or quantitatively, to varying sources in the processing conditions. Research work related to process sensitivity analysis of Ohmic heating processes, including electrical conductivity, particle size, shape and concentration, viscosity of liquid, and production formulation are reviewed with examples.

Section 7 includes Ohmic heating applications as applied to different classes of foods. Applications to muscle foods (meat, poultry, and fish products), dairy products, fruits, and vegetables are discussed. In the meat area, beef, poultry, and pork have been the subject of a large number of studies; some attention has been paid to fish, in particular surimi, and these have been included in Chapter 18. Fluid and semi-fluid foods such as milk and eggs are considered one of the candidates for Ohmic heating.

Thermal processing is the most established method to achieve microbial safety and shelf-life stability of milk. High-temperature short time (HTST) and ultra-high temperature (UHT) are the most widely used techniques for liquid products. Conventional HTST and UHT processes tend to affect taste and texture of the products. Ohmic heating is considered one of better processes for this purpose as it causes rapid heating without the use of hot surfaces. These are detailed in Chapter 19. Fruits, vegetables, and their products are discussed in Chapter 20. Pasteurization of fruit

and vegetable products is one of the primary applications for Ohmic heating technology, with several commercial products available. Much of the product and process development has been done on commercial systems because of the physical size of the particulates that make small-scale work challenging. Examples of commercial products are given. Most Ohmic processes use conventional cooling prior to packaging; however, it is thought that hot filling presents an opportunity that has not yet been fully exploited.

Chapter 21 deals with commercially successful applications. Examples are given of commercial food products processed by Ohmic heating. Most are high-acid fruits and purees, but there are others that require sterilization followed by aseptic filling. These include milk and egg products that foul easily with conventional heat exchanger technology as well as some meat products. A number of nonpreservation examples are also presented in which the objective is to enhance yield and extraction or evaporation and thawing rates. It concludes with the advantages and disadvantages of Ohmic heating.

Section 8 deals with other applications of Ohmic heating where preservation is not the main focus. Chapter 22 covers blanching which is a minor heat treatment given to foods prior to conventional processing such as canning, freezing, and drying for the main purpose of inactivating the oxidative enzymes which would otherwise cause off flavors during storage. This chapter introduces Ohmic heating as an alternative heating technique for blanching, including how it is applied and how it differs from conventional blanching. Chapter 23 is devoted to Ohmic thawing and tempering of frozen food products, and the advantages and limitations of the technology for the purpose.

Commercial food products, such as prepared dishes, are mostly solid–liquid mixtures and are thermally processed using traditional techniques. Continuous aseptic processing has been a reality for homogeneous liquid foods. However it has come across many compelling challenges when applied for heterogeneous liquid–particle food products and have only been met with some success. Ohmic heating is a promising way for aseptically processing fluids containing large particles (i.e., equivalent diameter ranging from 1 to 30 mm). With this process, solids can often heat faster than liquids, a result impossible to achieve using other heating techniques. In Chapter 24, the continuous heat treatment of solid–liquid food suspensions using Ohmic heating is described in relation to particle properties, flow, and heat-transfer criteria. The limited factors for a transition from a batch to a continuous process and the beneficial aspects are also discussed.

One of the more interesting applications that have emerged in the early twenty-first century is the potential for Ohmic heating in long-duration space missions. Interest has grown in mankind's future in space, with attention being given to a potential lunar base, and manned missions to Mars. Such missions are likely to pose major challenges to life-support functions aboard space vehicles. These are detailed in Chapter 25.

Chapter 26 deals with Ohmic cooking and describes how combined Ohmic and conventional cooking of meat patties can improve the cooking process and product quality. The method is based on passing electric current through the meat patties causing internal heat generation in addition to the usual surface heating caused by the two plates of the grill. The cooking times of the meat patties using the conventional and modified cooking methods were compared showing that a decrease in cooking time of 50% can be achieved by the application of Ohmic heating.

Electro-freezing as a concept for promoting smaller ice crystal formation is discussed in Chapter 27. This chapter presents improvement of refrigeration processes by development of innovative methods with the application of high-voltage electrostatic field (HVEF). Theoretical and experimental studies on electro-freezing, freezing under combined electrostatic and magnetic fields, electro-thawing, and finally, storage under HVEF conditions are discussed.

Section 9 is focused on process validation issues related to the Ohmic heating processes. Chapter 28 addresses validation Ohmic sterilization system. In this chapter information is presented in a decision-making format, which should be useful to those involved with the setup of an aseptic processing or UHT processing system that uses Ohmic heater(s) for heating the product. From a validation point of view, it is assumed that the Ohmic system is simply a heating system and

no additional microbial effects as a result of passage of current are claimed. A complete processing system will consist of supplementary and ancillary equipment that forms the overall system. Although the system is designed around Ohmic heating, conventional heat exchangers will be a part of the overall system. Although none of these decisions can be ignored, the scope of this chapter is limited to equipment used to pump, sterilize, cool, and deliver product(s) to the filler. Chapter 29 discusses the biological validation of Ohmic heating processes. Ensuring commercial sterility of continuously processed foods containing particulates cannot be based on conventional in-container thermal process calculations because time–temperature measurement in particulates is not possible as they move within the aseptic and/or Ohmic processing systems. In the absence of the physical means for temperature measurements, biological validation appears to be the only alternative available to evaluate efficacy of the process.

The regulatory issues related to Ohmic sterilization processes are discussed in the final chapter (Chapter 30). The regulatory details of operating aseptic processes are discussed, pointing out details important to Ohmic heating. Its purpose is not to detail all the provisions of the regulations, but to indicate generally what is expected in the processing and handling of foods specifically undergoing aseptic Ohmic treatment.

I would like to thank Navneet Singh Rattan for his voluntary assistance in the formatting and final stage editing of the manuscript. Further, I would like to thank the co-editors who have contributed extensively for the scientific, engineering, and editorial aspects of the book. My final thanks goes to all contributors (almost 50) to this volume for enriching the different chapters with their professional, scientific, technical, and engineering experience.

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Editors



Dr. Hosahalli S. Ramaswamy holds both a BS (Bangalore) and an MS (CFTRI, Mysore) from India, and an MS and PhD (University of British Columbia—UBC) from Canada. He has postdoctoral research experience at UBC (3 years) and industrial postdoctoral fellow at Okanagan Dried Fruits (Canada). He joined McGill University, Canada, in 1987 and has been continuing at McGill as professor of food processing. During the 25 years at McGill University, he has established a very strong research program in several areas of postharvest technology and food processing: thermal processing (conventional canning, agitation processing, microwave processing), aseptic processing, Ohmic heating, ultra-high-pressure processing, computer simulation and modeling, and the use of artificial neural network for process calculation, characterization, kinetics, optimization, and control.

Dr. Ramaswamy is active in food process engineering research and has published over 300 papers in refereed scientific journals, presented over 400 papers at conferences, and has been an invited keynote speaker at several international conferences. Dr. Ramaswamy has been a professional member of several societies: Canadian Institute Food Science and Technology (Canada); Institute of Food Technologists, USA; American Society of Agricultural Engineering (USA); Canadian Society of Agricultural Engineering; Institute for Thermal Processing Specialists (USA); Association of Food Science & Technology (India). He is an editor of *Journal of Food Engineering* and editorial board member of several international journals.

Dr. Ramaswamy has been conferred several prestigious awards: 1999 W.J. Eva Award by the Canadian Institute of Food Science and Technology for his outstanding contribution to the Institute and research; 2002 John Clark Award of Canadian Society of Agricultural Engineering for his outstanding contribution to society and research in the area of food process engineering; Fellow of the Association of Food Scientists and Technologists (India) and Outstanding Alumnus award from the Central Food Technological Research Institute (India); 2007 CIFST (Canadian Institute of Food Science and Technology) President's Award and in 2007, Fellowship of the Canadian Society of Bioresource Engineering, Merit Pin of IFTPS (Institute of Thermal Processing Specialists), and Fellowship of CIFST in 2013. He has served as a member of the select expert committee on Food Engineering and Processing of Canada, coordinator of Canada's Standard Committee on Retort Pouch Products and 2006–2008 Agriculture Canada Research Grant Selection Review Panel, board member of CIFST. Recently, he was responsible for winning the bid to bring the 2015 International Congress of Food Engineering (ICEF12) to Canada, which will be held in Quebec City under his Chairmanship.



Dr. Michèle Marcotte is currently the director of Research and Development at the Eastern Cereal and Oilseed Research Centre (ECORC) located at Agriculture and Agri-Food Canada in Ottawa. Michèle obtained a bachelor's in chemical engineering

(Laval), a master's in food engineering (Alberta), and a PhD in food processing (McGill). She started as a professional engineer at Agriculture and Agri-Food Canada at the AAFC's Food Research and Development Centre located in St. Hyacinthe where she held a successful career for 21 years as a section head of food preservation technologies; a research scientist in Food Processing and Engineering; an advisor to the Director General of the Food Safety and Quality National Science Program. She supervised several cooperative and graduate students in her laboratory. She authored and coauthored more than 60 peer-reviewed papers, 120 conference papers, and 45 research reports. In February 2009, the Quebec Order of Engineers that regroups more than 50,000 engineers featured a cover story in its monthly magazine on the role of engineering for food safety. Dr. Marcotte also developed a unique two-step drying process for cranberries that was implemented commercially in Quebec. Other significant developments include a prototype pilot oven for the optimization of baking and computer software to establish cooking-cooling cycle for meat products.

In 2009, Dr. Marcotte became the science director based in Ottawa at ECORC and responsible for managing one of the seven AAFC national science priorities titled: "Food and Health." Michèle was president of the Canadian Institute of Food Science and Technology (2006–2007). She is the Canadian representative of the International Association on Engineering and Foods (IAEF) and the International Union of Food Science and Technology (IUFoST). Dr. Marcotte received nine significant awards/prizes: (1) AgCellence Prize from Agriculture and Agri-Food Canada (Innovation) in 1998; (2) two André-Latour Innovation Prizes (1999–2000) of the Foundation INITIA; (3) the prestigious Excellence Prize of Treasury Board from the Canadian Public Service of the Government of Canada in 2000; (4) the Federal Partnership for Technology Transfer (FPTT) in 2003; (5) the Excellence in Research Prize from the Governor's Foundation of Agriculture and Agri-Food Canada in 2004; (6) the John Clark Award of the Canadian Society of Biological Engineers (CSBE) in 2010; (7) Agriculture and Agri-Food Canada Research Branch for the 125th Anniversary Celebration for her research contribution in food processing and engineering; and finally (8) the W.J. Eva Award of the Canadian Institute of Food Science and Technology (CIFST) for her outstanding contributions to engineering applied to food systems through service in research, training, and management in 2012.



Dr. Sudhir K. Sastry is professor in the Department of Food, Agricultural, and Biological Engineering at the Ohio State University. He obtained his BS at the Indian Institute of Technology; and his doctoral degree in mechanical engineering at the University of Florida. He was on the faculty at Penn State University for seven years, until joining Ohio State University in 1987. He spent sabbatical leave with Nestle in 1997–1998.

His research interests include Ohmic heating, aseptic, high pressure and pulsed electric field (PEF) processing, the influence of moderate electric fields on biological materials, and the safety of fresh produce. He has published over 170 papers, six patents, and a book titled *Aseptic Processing of Particulate Foods*. Two other books are forthcoming in 2013.

Among the recent projects led by Dr. Sastry is one on the Safety of Foods Processed Using Four Alternative Processing Technologies, wherein the safety assurance of products treated by Ohmic, microwave, high pressure, and PEF processing were addressed. Project information is available at: http://www.oardc.ohio-state.edu/sastry/USDA_project.htm

He has recently completed a project on Quality of Foods Processed Using Selected Alternative Processing Technologies, in collaboration with NC State, UC-Davis, Washington State University, and the US Army Natick Soldier Center.

He also recently completed a project for NASA, where he and his colleagues developed new, reusable food packaging for NASA's lunar and Mars missions. Among Dr. Sastry's inventions include a new, environmentally friendly produce peeling process, and a pH sensor that can be operated under extreme pressures.

Information on Dr. Sastry's projects may be accessed through his research group's website: <http://www.oardc.ohio-state.edu/sastry/>



Khalid Abdelrahim obtained his graduate degrees in food science from McGill University (Macdonald Campus), Montreal, Canada. He was a postdoctoral research associate at the Center of Aseptic Processing and Packaging Studies (CAPPS) at North Carolina State University (Raleigh, North Carolina).

Khalid started his professional career in 1996 at the National Food Laboratory, Inc (Dublin, California) on the contract of the National Food Processors Association at the time (currently the Grocery Manufacturers Association [GMA]). During 1998–2002, he went on to work with The Pillsbury Company, General Mills (Minneapolis, MN) where he was the process authority for the International Division.

He was with Campbell Soup Company (Camden, NJ) during the period 2002–2011, where he was a process authority for Campbell's Global aseptic operations. He was instrumental in the development and filing processes for aseptic processing of low-acid soups containing particulates. He was recognized with the Campbell's CEO Award for enabling Campbell to be the first food processor to market low-acid aseptic soups in North America under the Gardennay, Select Gold Label, and V8 brands. Furthermore, he developed and filed the first Ohmic heating process for Campbell Soup with the Food and Drug Administration.

Khalid is currently the thermal processing manager and process authority for Nestle USA and Nestle Canada (Glendale, CA) since 2011. He is responsible for the thermal process support of the Coffee Mate, NesQuik, Carnation Evaporated Milk, Libbey's Pumpkin, and so on.

Khalid is a member of the Institute of Thermal Processing Specialists (IFTPS), Institute of Food Technologists (IFT), and the Canadian Institute of Food Science and Technology (CIFST).

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Section 1

Basics of Ohmic Heating

1 Overview of Ohmic Heating

Sudhir K. Sastry

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1.1 HISTORY

In 1827, Georg Ohm published his treatise: *Die galvanische Kette, mathematisch bearbeitet* (*The Galvanic Circuit Investigated Mathematically*) where he described what is today known as Ohm's law. Thereafter, in 1841, James Prescott Joule showed that electricity flowing through a conductor resulted in the generation of heat. Although both these investigators faced skepticism and initial lack of acceptance of their results, their work has contributed directly to the development of today's embodiments of Ohmic, or joule effect heating.

In the 1800s, a number of patents sought to exploit the heat generation effect within flowable materials (Anderson and Finkelstein, 1919). The "electric pasteurization" process (Prescott, 1927) was used for milk treatment in six states in the United States in the 1930s. Thereafter, the technology languished for a number of years, only seeing sporadic application for blanching (Mizrahi et al., 1975).

In the 1980s, Ohmic heating was introduced by APV, who licensed the technology from the Electricity Council of Great Britain (Biss et al., 1987). This was an era of great interest in the aseptic processing of particulate foods, which was then being approached principally via indirect heat exchange. Conventional heat exchange technology for solid-liquid mixtures had always been (and still is) limited by slow heat penetration rates within the solid phase. Even within the liquid phase, the demands of entraining solids within liquids without phase separation necessitated the use of viscous liquids, thereby sacrificing liquid-phase heat-transfer rates as well. In particular, for equipment such as scraped (swept) surface heat exchangers, the residence time distribution of the solid phase was found to be considerably wider than conventional laminar flow. The net result was that after many years of research, sterility could be assured, but there was a potential risk of sacrificing quality. The intervening years have seen some commercialization of soups with small particulates, however, for large particulates, improved technology is necessary.

Ohmic heating has always been seen to fit this niche; its capability of achieving rapid and relatively uniform heating rates has made it an attractive option in the processing of particulate foods. In this respect it has shown advantages over other electrothermal methods of microwave, radiofrequency and induction heating, all of which suffer in one way or another with lack of uniformity.

This promise led to the development of a consortium led by Land-O'-Lakes to set up a pilot processing facility in Minnesota during the early 1990s. Although that facility closed without resulting in commercialization, later that decade a product was launched in the United States, and a liquid egg processing facility used Ohmic heating technology for a number of years. A number of new manufacturers have further developed the technology since, and the cost of Ohmic heaters per kilowatt of electrical energy has declined greatly over the years. At the time of writing, there are a significant number of Ohmic heating facilities in Europe, Japan, Mexico, South America, and

elsewhere, processing a variety of products, most notably fruit slices and large fruit pieces in syrup. Other applications also exist, including the processing of surimi products and panko bread making.

A key aspect in the development of less expensive equipment has been the advent of solid-state power supply technology, such as the Integrated Gate Bipolar Transistor (IGBT) around 1997, which were used as drivers for appliances. These devices have substantially altered the cost and footprint of heaters. A further benefit has been the near-elimination of electrolytic effects via frequency control. A parallel development from Electricité de France, has been the development of improved materials (dimensionally stable anodes) which have enabled operation at the European power frequency of 50 Hz.

1.2 PRESENT STATUS AND FUTURE OUTLOOK

Ohmic heating technology is clearly establishing a foothold in the food industry, in an era where competition from various successful and better-advertised nonthermal technologies have come into prominence. Two notable technologies, high-pressure processing and pulsed electric fields (a sister technology to Ohmic) have garnered much attention in recent years. However, in and of themselves, nonthermal methods inactivate neither bacterial spores nor enzymes. Indeed, it is only in combination with heat that high-pressure processing has recently achieved a letter of no objection from FDA; thus, the term pressure-assisted thermal processing is more appropriate. Ohmic heating has none of these limitations, being a thermal technology; however, it becomes essential to manage the heat treatment properly to ensure that the negative aspects of thermal treatment are minimized.

Although Ohmic heating has received most attention as a sterilization or pasteurization treatment for particulates, it is far from being a mature technology, even when restricted to this application. The number and types of potential designs for Ohmic heaters have great variety, and may be tailor-made to individual applications. Indeed, much is left to the designer's creativity, and the variety can only increase as the technology develops. A key feature is that there is room for creativity both from the equipment designer's and product developer's perspective. Most Ohmic heaters are built to operate over a range of electrical conductivities. These can either be high-voltage, low-current devices (usually with electric fields in line with the flow), or low-voltage, high-current devices, with fields typically across the flow. The former are intended to operate with high electrical conductivity fluids, typically products such as soups, stews, or preparations containing sauces with sufficient salt to provide electrical conductivity. The latter are intended for relatively low electrical conductivity fluids, such as water or foods/beverages without ionic additives. Both types of designs are now commercially available, and it is possible to heat foods over a wide range of electrical conductivity. Further, for a given heater, it is possible to develop products that may be heated within it by changing (within product limits) the electrical conductivity of the Ohmically processed component. Given that ionic food components enhance electrical conductivity, and nonpolar components, such as fats, decrease it, it is possible to modify formulations to fit a particular heater's operational range. This design interplay between product and package is still in its infancy, but holds promise for future development.

The number of potential applications of electrothermal processing is vast: the electric fields associated with Ohmic heating have been found to have significant nonthermal effects on cells, paving the way to a wide range of improved food processes, known collectively as moderate electric field (MEF) processing. Examples of such applications have been potential improvements in blanching (Sensoy and Sastry, 2004a), extraction (Sensoy and Sastry, 2004b), drying (Wang and Sastry, 2000; Salengke and Sastry, 2005), juice expression (Wang and Sastry, 2002), frying (Salengke and Sastry, 2007), detection of starch gelatinization (Wang and Sastry, 1997), acceleration of fermentations (Cho et al., 1996; Loghavi et al., 2007), and peeling of produce (Wongsa-Ngasri and Sastry, 2009).

In recent years, Ohmic technology has been investigated for long-duration space travel applications. The extreme constraints of long-duration space travel, including high cost, need for low-volume systems, and the availability of electric power as the principal energy source within spacecraft, has

resulted in an ideal situation for utilization of Ohmic heating. A recent NASA project (Pandit et al., 2008) has resulted in the development of an Ohmic pouch, with electrodes used to heat food, which could thereafter be used to sterilize waste.

At the time of reintroduction of Ohmic heating in the 1980s, it was thought that electricity had no nonthermal effects on bacteria and that the efficacy of the process was itself principally thermal. Close to the turn of the century (Sastry and Barach, 2000), it began to be recognized that some nonthermal effects might exist, but overall, the view remained that it was a thermal process and that there was no need to invoke any nonthermal effects in a process filing. One of the major difficulties in this regard has been the convincing demonstration that a given experiment has legitimately compared thermal and nonthermal effects. In such cases, it is critical that experiments be conducted in such a way that thermal history of conventional and Ohmic samples is matched as closely as possible. Many studies in this area have failed at this exacting requirement, and consequently cannot be considered reliable.

Since that time, some investigators have refined their experimental techniques to the extent that there is now a growing body of evidence of a nonthermal effect of Ohmic heating, both on vegetative cells and bacterial spores (Cho et al., 1996; Pereira et al., 2007; Somavat et al., 2008; Sun et al., 2008). Further, and equally interesting, these phenomena have a frequency dependence, which may pave the way to significantly reduced thermal processes in the future. Indeed, Ohmic heating technology has recently found application in inactivation of *Legionella* within a hospital water supply in France, and has been found to be more effective than conventional thermal treatment at the same temperature.

Equally interesting has been the finding that Ohmic heating also can accelerate the inactivation rate of certain enzymes (Castro, 2007), especially those with a metallic prosthetic group. If future studies confirm this and the above trends, Ohmic heating may have a bright future as a reduced thermal process.

That Ohmic heating has survived; indeed thriving despite the presence of negative comment and competing technologies is evidence of its fundamental soundness and robustness as a technology. The abundance of opportunities afforded by its expanding development promise an exciting future for the food and bioprocess industries.

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2 Why Ohmic Heating? Advantages, Applications, Technology, and Limitations

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2.1 THE FUNDAMENTAL PRINCIPLE OF OHMIC HEATING

When electrical current flows through a conductor, the motion of charges within the material results in agitation of molecules (or atoms) therein. This results in increased temperature. Within metallic conductors, the moving charges are electrons; however within food materials, the charges are usually ions or other charged molecules such as proteins, which migrate to the electrode of opposite polarity. A schematic diagram of this mechanism is illustrated in Figure 2.1.

Ohmic heating will occur regardless of whether or not the current is direct or alternating. Nevertheless, all known food applications involve alternating polarities. This is dictated by the occurrence of electrolysis within DC systems, and the ready availability of alternating power. Increasingly, however, power supplies use a variety of frequencies that may be different from the local power supply.

The rate of heat generation within the material may be characterized by the following equation:

$$u''' = E^2 s \quad (2.1)$$

The above expression provides the basis for design of devices and formulation of products for Ohmic heating. The electric field strength ($E \simeq V/l$) may be varied by the designer by changing either the applied voltage, or the interelectrode gap l . The effective electrical conductivity, σ is a function of temperature, frequency and product composition, and may be increased by addition of ionic compounds such as salts or acids, or decreased by addition of nonpolar components such as emulsified lipids. This suggests that for a product of a given range of electrical conductivity, it is possible to design a heater to successfully heat it Ohmically; and conversely, for a given heater design and operational variables, it is possible to modify a product (within limits of sensory acceptability) to enable its heating.

An important point is that for Ohmic heating to occur, the electrical conductivity must be non-zero. This means that completely nonpolar materials, such as oils, which do not conduct electricity, cannot be heated Ohmically. However, most food materials are aqueous-based, and possess some

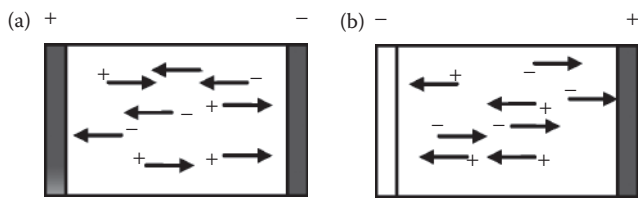


FIGURE 2.1 Illustration of ionic movement during Ohmic heating of an aqueous-based material. (a) During one half-cycle, when the ions within the product move to the electrode of opposite polarity; (b) movement when electrode polarities are reversed.

electrical conductivity (albeit low), and can therefore be heated. Indeed, it is possible to heat most water supplies, even when the electrical conductivity is low; since it is possible to use devices with low electrode gaps, and to increase electric field strengths to compensate.

Another notable feature of Ohmic heating is that the electrical conductivity of foods typically increases with temperature, since fluids decrease in viscosity with increasing temperature, thus the drag on moving ions is reduced at high temperatures. A typical example is shown in Figure 2.2 for Southwestern corn soup.

In many situations, and particularly for liquids, the electrical conductivity is a linear function of temperature, and may be modeled as

$$s = s_0 [1 + mT] \tag{2.2}$$

For solid materials, particularly those in which the cell structure is intact, the electrical conductivity is not necessarily linear, being dependent also on electric field strength. This is because of cell breakdown by electropermeabilization. Additionally, starch suspensions undergoing gelatinization show peaks in their electrical conductivity–temperature curve that correspond to specific differential scanning calorimeter thermograms (Wang and Sastry, 1997).

Electrical conductivity will be dealt with in more detail in a later chapter, and therefore is not covered here. A further, detailed discussion is also provided by Sastry (2005).

The background information presented above encapsulates a number of the concepts of Ohmic heating, and illustrates the special features and arguments for its use in specific situations.

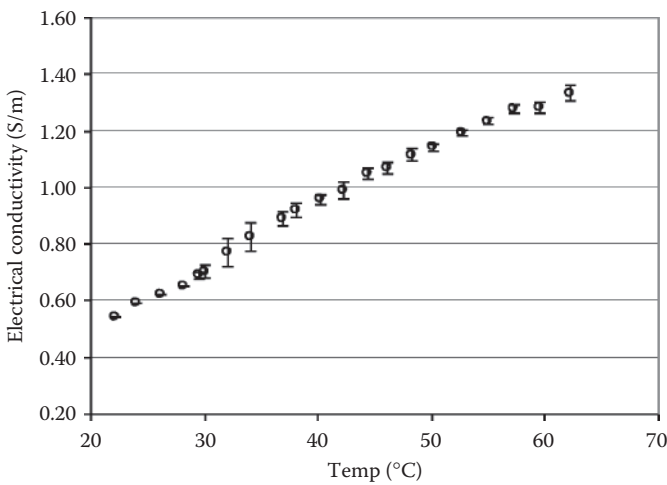


FIGURE 2.2 Electrical conductivity of Southwestern corn soup as affected by temperature.

2.2 WHY OHMIC HEATING?

1. *Uniformity of heating.* Since Ohmic heating relies on internal energy generation, solid pieces within a solid–liquid mixture may be made to heat at the same rate as the fluid. This is a significant advantage over conventional heating, where heat is transferred from an external medium through heat exchange walls and a carrier fluid before reaching the solid phase. Ohmic heating also has considerable advantages in heating uniformity over microwave and radiofrequency heating, since both those methods involve the application of complex electric fields that are difficult to characterize locally within a multicomponent material. Thus, these methods result in heating patterns wherein cold spots change locations and are difficult to characterize.

An example of how a product may be formulated to improve Ohmic heating uniformity is shown in Figure 2.3 where it may be seen that more closely matching electrical conductivity of phases results in more uniform heating. Indeed, even in situations where the solids' electrical conductivity is lower than the fluid, it is possible for the solids phase to heat faster than the fluid, provided its volume fraction is sufficiently high (Sastry and Palaniappan, 1992). Further evidence of this effect is often seen in Ohmic sterilization systems, wherein the fluid temperature has been observed to rise within the holding tube, indicating the presence of hotter solids within it.

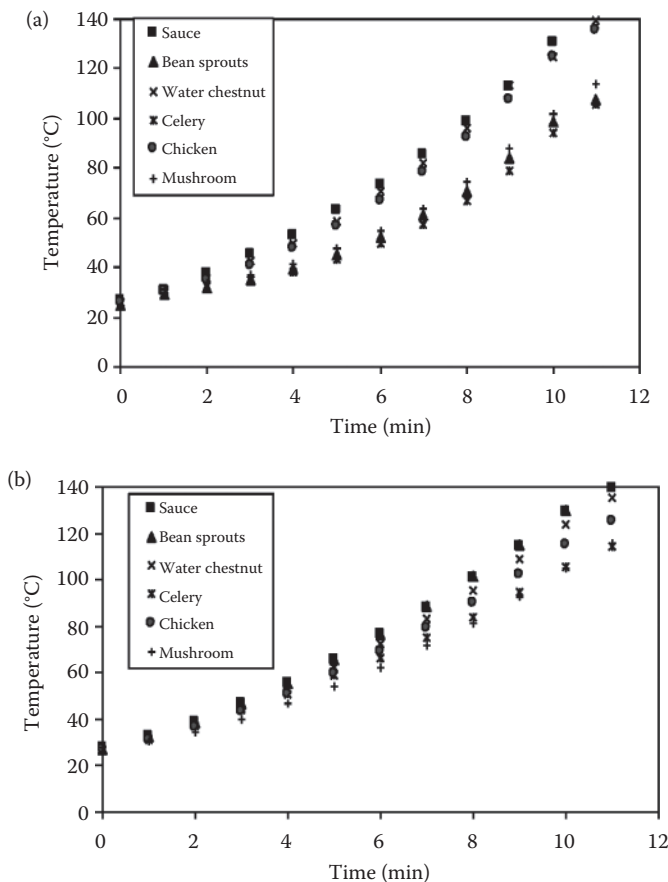


FIGURE 2.3 (a) Ohmic heating rates of various untreated components of chicken chow mein heated together; (b) Ohmic heating rates when components are blanched with sauce to match electrical conductivities more closely.

The above features suggest that Ohmic heating is suited to sterilization applications, in particular for those with high solids concentration. This continues to be a major interest; indeed most Ohmic heaters are largely focused on this application.

2. *No theoretical upper temperature limit.* Unlike conventional heat exchange applications, where the medium temperature is the highest attainable, Ohmic (as well as microwave and radiofrequency) heating involves internal energy generation, and may achieve temperatures far in excess of conventional processing. While there is no set theoretical temperature limit, in practice, heat losses increase as temperature rises until steady state is achieved.

This feature has both positive and negative implications. On the positive side, Ohmic heating may be used to heat rapidly past the temperature zones of undesirable reactions (e.g., temperature range of maximum protease activity in surimi products); something not possible with conventional heating. However, if the process is not properly controlled, it is possible for temperatures to rise to boiling levels, which cannot be contained by the system back pressure.

3. *Controllable heating rate.* As presented in Equation 2.1, the rate of heat generation may be altered by altering electric field strength. This is typically accomplished online by controlling the applied voltage. It is also possible to implement constant power control (fairly typical) or constant current (needed when a certain maximum current should not be exceeded).

These controls have another advantage: the possibility of direct online monitoring of power input into the system regardless of control strategy. This can be advantageous in a number of ways. One is in determining if the temperatures measured at Ohmic heater outlets are accurate: the measured power may be compared to that required to heat the product, to determine if the appropriate temperature rise has been achieved. One final control option is the use of current to monitor temperature. As Equation 2.2 shows, the electrical conductivity typically shows a linear relationship with temperature; thus for a given product and geometry, the current (directly proportional to electrical conductivity) may be used for monitoring product temperature without use of temperature probes. The temperature so measured is representative of the average product temperature, rather than a point determination.

4. *Cost.* When Ohmic heating was reintroduced in the 1980s, cost was a concern to many potential buyers. The units of the time operated at mains frequencies, were with large power supplies for relatively low-power output. These devices had large footprints and low throughput, making the choice less attractive.

The cost of Ohmic heaters has declined greatly over the past ten years or so. This is due in part to the advent of less expensive solid-state power supplies, and to the increasing number of manufacturers in the industry.

5. *Energy efficiency.* A major advantage of Ohmic heating is that nearly all the energy delivered to the food is used. Efficiencies of 90% and above are common. This is in contrast to microwave heating, which is typically only 50% efficient (~67% energy efficiency in the magnetron, and about 80% delivery efficiency through waveguides). Thus, long term, Ohmic is likely to be an attractive option in an industrial setting.

Except where hydroelectric or wind power is abundant, electricity is more expensive than fossil fuels; however at a plant level, it involves cleaner operation and there is no need for reliance on boilers. A common approach, when heating liquid products, is to utilize product-to-product regeneration for product preheating, followed by a final Ohmic heating step, thereby reducing the total electrical demand on the system.

Energy efficiency is a critical criterion in long-duration space missions, where space is at a premium. Since it currently costs about US\$ 22,000 per kg of material placed in orbit, so reduction of system mass is critical. The commonly used approach at NASA is the reduction of all attributes of a device to a common unit of equivalent system mass (ESM). The concept encapsulates the idea that anything placed within a spacecraft increases the total

volume of the spacecraft, and thus its total mass. Further, any energy-using device results in the need to increase the size of the vehicle's power plant, thereby increasing mass. A need for cooling requires an increase in the size of external radiators. The end result of a variety of such considerations results in a mass penalty for any new device, thus all devices serving a given function may be compared based on their ESM values.

A comparison of food warming devices (Pandit et al., 2008) for the upcoming Orion lunar vehicle missions showed a significantly lower ESM for an Ohmic device (839 kg) compared to the suitcase heater (3475 kg), a conventional external electric heating device. Ohmic heating is a logical choice for thermal treatments on Mars missions, not only for this reason, but also given that the most likely available energy source within a space vehicle is electrical. Further, technologies such as microwaves are not allowed within space applications due to interference with radio signals. Even if allowed within a space environment, microwaves would result in larger ESM values due to their relatively low-energy efficiency and need for bulky waveguides.

Recent work has resulted in the development of a dual-use Ohmic heating package, which can be used to contain and heat food in transit and thereafter be used to contain and sterilize waste. This work has been detailed by Jun and Sastry (2007) and Jun et al. (2007). As a further extension of this concept, it is possible to contain and sterilize foods that may be grown during a long-term lunar or Mars stay.

6. *In-situ process monitoring and feed-forward control.* As discussed under item 3 above, Ohmic heating offers the possibility to monitor energy inputs online, and use these for making intelligent process decisions, or to control the process at downstream locations (feed-forward control). An example of this is in the processing of foods that are solid-liquid mixtures, illustrated below in Figure 2.4 for a three-heater system.

Another feed forward control application involves the detection of particles of unusual electrical conductivity within a liquid-particulate mixture. It has been shown in the literature (Sastry and Palaniappan, 1992, Salengke and Sastry, 2007a,b) that the greatest potential safety hazards during Ohmic processing of a solid-liquid mixture is the presence of a single or small number of inclusion particles of electrical conductivity significantly different from their surroundings. One processing strategy in this case is the online detection and possibly, ejection of such outlier particles. Indeed, such detection is possible by a simple online detector (Figure 2.5), which continuously monitors the electrical conductivity of solid-liquid mixtures. The device passes a small electrical current perpendicular to the product flow path, and uses the measurement of the current as an indicator of product

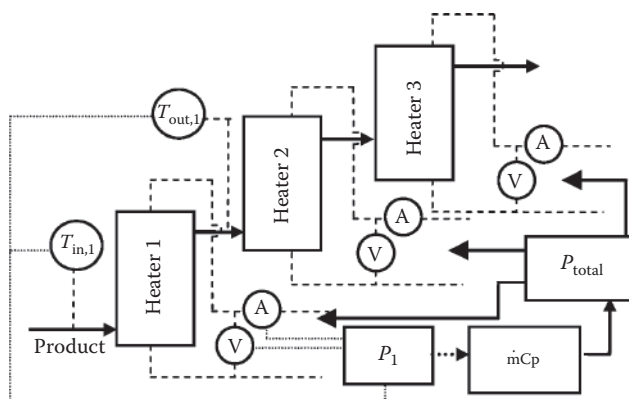


FIGURE 2.4 Schematic of feedforward control for a three-heater system. The power measured in heater 1 is used for calculation of thermal mass flow rate and used to control the total power to the system.

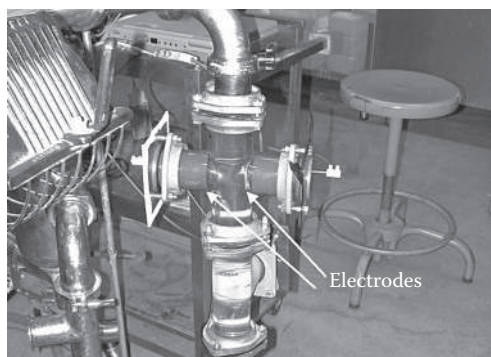


FIGURE 2.5 Device for online monitoring of electrical conductivity of a solid–liquid mixture.

conductivity. When a particle of unusually high or low conductivity passes through the detector, the measured electrical conductivity changes, hence, producing a detectable change in current. This may be used to pre-screen components that are outside specifications and actuate a downstream diversion valve. This approach may be valuable in assuring food safety and avoiding product rework.

A cautionary note is also in order for those intending to use Ohmic heating for its capability of rapid heating. While rapid heating can produce outstanding product, the key consideration is stability. Products may well heat at rates faster than the response time of the temperature measurement device. This could result in a control system that is unable to keep up with heater speed, and a consequently unstable operation. Such approaches may be used where product variations and other perturbations are minor.

7. *Wide variety of designs and heater sizes.* Ohmic heaters may be designed in a variety of ways, either static or continuous. This is further illustrated in later chapters on laboratory units and Ohmic heating for space applications, where it is seen that even a food package may serve as an Ohmic heater if it is configured in a manner such that the product is part of the electrical circuit. Additionally, sizes may be widely variable, ranging from tens of tons per hour to microscale dimensions. For food applications, the limits are typically set by operational constraints. At the high end, power availability is the principal constraint; at the low end, the dielectric breakdown strength of aqueous solutions and fouling of electrodes are key constraints.

In the continuous flow mode, two major designs exist, the in-line field and cross-field variations, each of which may be accomplished in various ways. These are illustrated in Figure 2.6. The coaxial field heater has the electric field aligned perpendicular to the flow.

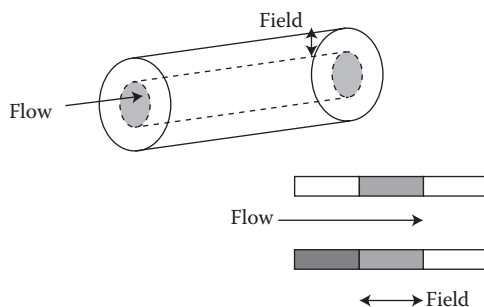


FIGURE 2.6 Two possible designs of continuous flow heaters. Top: coaxial cross-field heater. Bottom: aligned field heater.

This device is preferred in situations of low product electrical conductivity, when high field strengths are needed, and current flow needs to be maximized. Product examples in this case involve those with low ionic concentrations, for example, municipal water and sugar syrups. An example of this design is described by Herrick et al. (2000). The other design category, the aligned field, is used when electrical conductivities are high, as is typical of products containing salt. In this case, the product conducts electricity readily, and the current must be kept to manageable levels to avoid tripping circuit breakers. These devices are also characterized by high interelectrode gaps and consequently, lower electric field strengths.

While the above are major categories, there are a potentially infinite number of variations, limited only by the designer's imagination and ingenuity. It is not unreasonable to state that the design of Ohmic heaters is in its infancy.

8. *Nonthermal effects of electric field.* Electrothermal methods have attracted much attention due to their ability to heat foods volumetrically. However, knowledge of thermal inactivation kinetics of microorganisms was limited. Palaniappan et al. (1990), reviewing the literature on the effect of electricity on microorganisms, found that many prior studies were inconclusive due to poor temperature control during electrothermal treatments, resulting in the inability to eliminate temperature differences during comparisons between purely thermal and electrothermal treatments. Cho et al. (1999) showed that inactivation of *Bacillus subtilis* could be accelerated under Ohmic heating, compared to conventional heating under identical temperature histories. Nevertheless, the body of knowledge was not sufficient to draw general conclusions, thus the Institute of Food Technologists' report to the FDA suggested that there was no need to consider extra-thermal effects in filing for Ohmic heating processes (Sastry and Barach, 2000).

More recently, a growing body of evidence, collected under carefully controlled conditions, indicates that bacterial spores show increased inactivation during Ohmic heating in comparison to purely thermal treatments at the same temperature (Pereira et al., 2007; Somavat et al., 2008). Additionally interesting effects have been found with frequency: vegetative cells have been found to respond most strongly to lower frequencies (Loghavi et al., 2007, 2008), while inactivation of *Geobacillus stearothermophilus* was most accelerated at frequencies around 10 kHz (Somavat et al., 2008), as illustrated in Figure 2.1. Further confirmation of enhanced electrothermal lethality for pathogenic spore formers such as *Clostridium botulinum* could pave the way for significant improvements in commercial food sterilization processes, and provide a new inactivation tool against bioterrorism.

LIST OF SYMBOLS

- E** Electric field strength (V/m)
m Temperature coefficient of electrical conductivity (EC^{-1})
 u''' Rate of heat generation per unit volume (W/m^3)
 σ Electrical conductivity of material (S/m)
 σ_0 Electrical conductivity of material at $0^\circ C$ (S/m)

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Section 2

Electrical Conductivity

3 Electrical Conductivity

Importance and Methods of Measurement

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3.1 INTRODUCTION

Ohmic heating occurs when an alternating current is passed through a food that is electrically conductive, therefore heat generation takes place volumetrically, and the electrical energy is directly converted into heat causing a temperature rise. This system is comparable to an electrical circuit, which is comprised of a resistance and a source of current at an appropriate voltage gradient. The food product placed between the two electrodes acts as the resistance when an alternating current passes through it. In other words, the food is made part of an electrical circuit. Other synonyms used in the literature to describe this principle of heating are: direct resistance heating, Joule effect heating, electro-conductive heating and electro-resistive heating. Classical heat-transfer mechanisms such as convection or conduction are minimal. It offers an alternate way to rapidly heat food, bypassing conventional heating systems. Other direct volumetric heating techniques are also available as classified into three categories by Pain et al. (1995): steam (e.g., injection and infusion), radiation (e.g., infrared, microwave, and radio frequency) and the Joule effect in which Ohmic heating is found. Ohmic heating is comparable to microwave heating without an intermediary step of converting electricity into microwaves through the magnetron before applying to the product. Varghese et al. (2012) reviewed the Ohmic heating technology and its application in food processing and concluded that this technique is especially advantageous in processing semi-solid, particulate foods. It has proven advantages over conventional thermal processing and novel thermal alternative

technologies. However, the success of Ohmic heating depends on the rate of heat generation in the system, the electrical conductivity (EC) of the food, electrical field strength, residence time, and the method by which the food flows through the system.

EC refers to the ability of a material such as food to transport an electric charge. By introducing an electrical voltage difference across a conducting material, the transferable charges will flow through the conductor that produces an electrical current (primarily alternating). The existence of the electrolytic component such as salt and acids in food materials, allows the electric current to pass through them. The passage of an electric current through food systems is the basis of the Ohmic heating technique, which generates heat internally within both liquid and solid phases and raises the temperature that can be used to sterilize food. The amount of generated heat is directly proportional to the current that is produced by the voltage gradient, and the EC of the food stuff (Skudder and Biss, 1987; Sastry and Li, 1996; Icier and Ilicali, 2004). Furthermore, the amount of the current that passes through the system depends on the EC or electrical resistance of the material in the system. Therefore, in an Ohmic heating process, EC can be considered the most important influencing parameter, as indicated by many researchers (de Alwis et al., 1989; Palaniappan and Sastry, 1991a; de Alwis and Fryer, 1992; Tulsian et al., 2008). The suitability of the materials for Ohmic heating can be determined by their electrical conductivities. EC can be considered a fundamental characteristic of all materials that may depend on other materials properties such as composition, soluble salt percentage, electrolyte mobility, and temperature (Benoit and Deransart, 1976; de Alwis and Fryer, 1992; Ayadi et al., 2004). Moreover, EC measurements can be used to detect compositional discrepancy and structural changes in food products (St-Gelais et al., 1995; Zhuang et al., 1997; Guerin et al., 2004). A liquid-particle food system is mainly being controlled by the EC of both solid and liquid phases.

The importance of EC of liquid and solid food phases during Ohmic heating has been demonstrated through experiments and simulation (de Alwis et al., 1989, 1990). Therefore, for designing a process for an Ohmic heating system, proper knowledge of electrical conductivities of foods under Ohmic heating conditions is essential.

3.2 IMPORTANCE OF EC

It is the EC or the overall resistance of food that controls the Ohmic heating rate. A proper balance between current and voltage is necessary which results in a desirable temperature rise in the product. In highly conductive materials such as metals, a large current will flow, but voltage gradient will be limited. In insulators or highly resistive materials like wood, there will be a negligible flow of current even when voltage gradients are extremely high. It is important to note that in both these conditions, the generation of heat will not be sufficient. Therefore, boundaries exist for the values of EC in order to obtain sufficient heat generation. If the electrical conductivities of food materials fall outside this region, it would represent a potential setback to the heating process. Most pumpable foods contain water in excess of 30% and other dissolved ionic species such as salts and acids, which render the food electrically conductive to benefit from Ohmic heating (Halden et al., 1990; Palaniappan and Sastry, 1991b; Marcotte et al., 2000; Tulsian et al., 2008). Pure fats, oils, alcohols, and sugars are not suitable materials for Ohmic heating. These substances are electrically too resistive. Highly conductive materials (e.g., very concentrated salt solutions) that allow most of the current to pass through are also not suitable. There is a certain operating region (Figure 3.1) of electrical conductivities for a successful Ohmic heating process, within a maximum and physically limited power (de Alwis and Fryer, 1992). However, there is sufficient flexibility to adjust food formulations by mixing highly conductive and resistive food ingredients so that the overall conductivity is optimal in order for the Ohmic heating process to be most efficient (Zoltai and Swearingen, 1996). Sastry and Palaniappan (1992c) have demonstrated that in a heterogeneous mixture, there is a higher rate of increase in EC of a potato particle as a function of temperature than for a carrier fluid of various electrical conductivities.

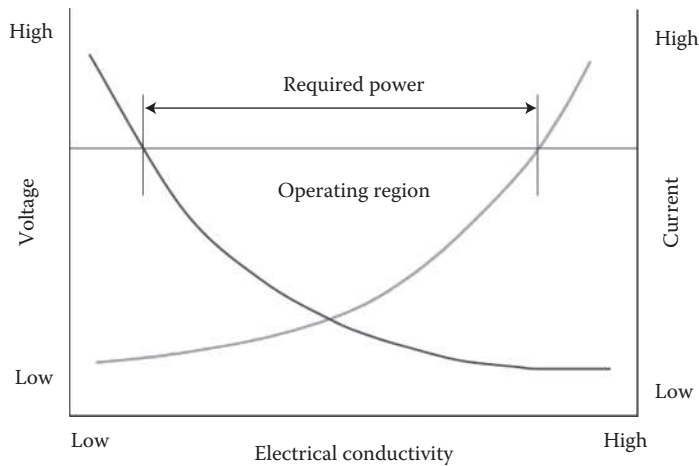


FIGURE 3.1 Operating region of EC.

The presence of any electrically insulating component in the food system can cause nonuniformity in the heating rate (Davies et al., 1999). Therefore, care must be taken with the preparation of formulations for Ohmic heating processes. Salt concentration in food formulations is another important factor. Because salt changes the electrical resistance of the food system, it has been reported that the Ohmic heating efficiency increases with salt concentration, which determines its heating rate (de Alwis and Fryer, 1992; Marcotte et al., 2000). Potato pieces were soaked in salt solutions at different concentrations by Palaniappan and Sastry (1991a). They found that the EC values increased with an increase in the concentration of salt, and hence the product temperature and heating rates. Similarly, the effect of salt diffusion into potato tissue was investigated by Wang and Sastry (1993), where they found that the EC profiles followed the salt concentration profile. A stronger relationship between the EC and the salt concentration was found when the amount of salt exceeded 0.01 g/cm^3 in the tissue. Use of high concentration brine resulted in nonlinear EC-T profiles during Ohmic heating. For modeling the EC of fish food emulsions (e.g., surimi), the salt content was included in the model by Yongsawatdigul et al. (1995) as an important parameter in their model for EC as influenced by food composition and temperature. The level of sodium chloride was found to significantly affect EC values in frozen seafood during Ohmic thawing, the treatment being more efficient at higher concentrations of salt (Luzuriaga and Balaban, 1996). In another study conducted in a water-based system, Marcotte et al. (2000) found that at low salt concentration the type of hydrocolloids will have an impact on EC values and temperature profiles. Furthermore, they reported that charged hydrocolloids such as carrageenan and xanthan are more efficient than starch for Ohmic heating. However, they concluded that with salt concentrations at or greater than 1%, the salt had a higher effect than the type of hydrocolloids in solutions.

Depending on whether the food system contains only liquid, solid, or mixture of liquid and solid with the presence or absence of other ingredients such as salt and spice, the heating behavior of the foods that undergo the Ohmic heating process are totally different. Precise knowledge of EC for a given food system is a key parameter for the food processors to design a safe thermal process while not over or under cooking the food. Therefore, during the last two decades researchers have tried different techniques to evaluate the EC of food components and food matrices. Owing to the large variation in physical properties of biomaterials, the reported values need to be cross checked and verified for an appropriate process design. In the following sections different approaches used to evaluate the EC of various food systems will be presented.

3.2.1 LIQUID FOOD CONDUCTIVITY

The earliest application of electricity started with the liquid food in late eighteenth century, where Jones (1897) used direct resistance heating for the heating of liquids followed by its early usage in milk pasteurization (Getchell, 1935). This method was successfully applied to milk pasteurization in five states in the United States, where by 1938 a total of 50 such units were constructed to serve consumers (Moses, 1938). However, as indicated by de Alwis and Fryer (1990), the method lost its credibility due to its high processing cost compared to other energy sources. The application of Ohmic heating for milk processing was revived by the Finnish company, Elecster Oy (Hallstrom et al., 1988), which introduced the Elecster process. In this process, raw milk was first preheated to about 115°C, then passed through an electrical heating tube to be electrically heated to 140°C. To prevent burning, the milk was kept under turbulent flow conditions.

However, in recent years, Ohmic heating has been applied to liquid foods by several researchers. Palaniappan and Sastry (1991b) studied the effect of temperature, solids content, applied voltage, and particle size on the EC of juices. Qihua et al. (1993) designed and fabricated an experimental Ohmic heating unit to measure EC of liquid food. Considering that the liquid foods contain different amounts of soluble solids such as salts and acids that can affect the conductivity of the system, the EC plays an important role in such systems. EC presents a measure of the total ion concentration in such a matrix.

Qihua et al. (1993) designed and fabricated an experimental Ohmic heating unit along with the necessary data acquisition system, to evaluate their performance under static and continuous operating conditions. An aqueous sodium chloride solution of 0.1 M concentration and fresh orange juice were used in the tests. In a static Ohmic unit, the liquid foods could be heated from 20°C to 80°C in about 20 s at a voltage gradient of 40 V/cm. The heating was reported to be uniform for all practical purposes and led to the measurement of EC of liquid as a function of temperature. They concluded that the bubbles formed during Ohmic heating should be given serious consideration, especially when the liquid temperature exceeds 50°C. In a steady-state continuous flow of Ohmic heating, the outlet temperature was automatically governed by the flow rate, properties of liquid, voltage gradient, and the configuration of the heating units. The most important parameters determining the outlet temperature were the voltage between electrodes and flow rate, which also affected the stability of the heating operation.

Marcotte et al. (2000) evaluated the electrical conductivities of different hydrocolloid solutions (starch, 4.3%; carrageenan, 1.7%; xanthan, 2%; pectin, 2.5%) with varying amounts of NaCl concentrations (0.25%, 0.5%, 0.75%, and 1%). They reported that at low salt concentration (<1%), the magnitude of EC values was largely influenced by the type of hydrocolloids, which may be related to the chemical structure and composition of these hydrocolloids. However, charged hydrocolloids such as carrageenan and xanthan were more efficient than starch upon Ohmic heating. With salt concentration at or greater than 1%, the salt effect was more important than the type of hydrocolloids in solutions. They also reported that the effect of added citric acid on electrical conductivities was small. EC can be affected by the nature of ions and the ionic movement of liquid samples (Palaniappan and Sastry, 1991b). Carrageenans are acidic hydrocolloids, which are always accompanied with counter ions. The structure of xanthan renders this hydrocolloid anionic. These charged compounds could explain their better efficiency upon Ohmic heating at low salt concentration. Most starches are usually a combination of amylose and amylopectin in different proportions. It is usually a neutral polysaccharide, which could explain it being the poorest performer upon Ohmic heating. Pectin is a polymeric carbohydrate composed of a chain of galacturonic acid units that are partially esterified as methyl esters. Therefore, it will be less charged than xanthan and carrageenan but more so than starch. The structure of these hydrocolloids can explain the specific Ohmic heating behavior at low salt concentration.

For high acid liquid foods containing low insoluble solid content, such as apple juice, EC changes with the concentration. The EC of concentrated apple and sour cherry juices were investigated by

Icier and Ilicali (2004) through an Ohmic heating system. They reported that the apple juice had lower EC values than sour cherry juice. This can be attributed to higher acid content of the sour cherry juice. Recently, the effects of Ohmic heating on the reduction of *Escherichia coli* O157:H7, *Salmonella typhimurium*, and *Listeria monocytogenes* in orange and tomato juice were investigated by Sagong et al. (2011). Orange and tomato juice were subjected to Ohmic heating with selected parameters including electric field strength from 10 to 20 V/cm while inoculated with *E. coli* O157:H7, *S. typhimurium*, and *L. monocytogenes* and treatment times varied from 0 to 540 s. They have found that the number of pathogens was reduced by increasing the electric field strength as well as increasing treatment time. The population of *E. coli* O157:H7 was reduced more than 5 log after 120, 210, and 540 s of treatment in orange juice with 20, 15, and 10 V/cm electric field strengths, respectively. Using tomato juice, levels of *E. coli* O157:H7 were reduced more than 5 log after 90, 180, and 480 s with the same electric field strengths. Similar phenomena were observed for *S. typhimurium* and *L. monocytogenes*, but *E. coli* O157:H7 was the most resistant to Ohmic heating treatment. The results of this recent study indicated that Ohmic heating is potentially useful for inactivation of pathogenic microorganisms and that the effect of inactivation depends on applied electric field strength, treatment time, pathogen species, and type of juice.

3.2.2 SOLID FOOD CONDUCTIVITY

The importance of the EC of the solid foods for the heating rates of food particles during Ohmic heating were established by de Alwis et al. (1989, 1990) through experiments and simulation. Considering the importance of the EC of solid foods several researchers have studied the EC of several solid foods. Basically, the same principles and techniques as for liquid foods have been used to evaluate the EC of the solid food materials. The heating behavior and the EC of solid foods can be adjusted by adding some percentage of salt if the solids of interest could be blended as puree such as carrot or potato puree. Minced meat may also be used to adjust the EC in case it has to be mixed with other ingredients in order to have a uniform food matrix in terms of EC for processing, to avoid over or under process of other materials in the food system.

Mitchell and de Alwis (1989) evaluated the EC of different meat (chicken and canned pet food) fruit and vegetable (pear, apple, potato, turnip, onion, tomato, pepper, mushrooms, cucumber, Brussels sprouts, parsnip, celery, Courgettes, leeks, and carrot) samples. They reported differences for the materials' EC measured with and without skin. For the materials with considerable fat and starch content as addressed by Halden et al. (1990), the melting of fats and starch transition as well as cell structural changes could affect the EC during Ohmic heating.

EC of potato, carrot, and yam samples was investigated by Palaniappan and Sastry (1991a). They reported that the EC increases linearly with temperature during Ohmic heating. Furthermore, they investigated the EC of the vegetable samples by immersing them in water and salt solutions. The EC of the samples decreased when they were immersed in water (which resulted from leaching of solutes), infusion of salt solutions increased EC. Since in Ohmic heating, the heating rates of the materials depend on their EC, they concluded that EC could be adjusted using water or salt solutions. As a result, the product's residence time during processing could be reduced by using high EC, which can be adjusted. However, if the properties of foods are not seriously influenced, adjustment of EC could be considered.

Shirsat et al. (2004a,b) measured the EC of a model meat emulsion and concluded that salt and other electrolyte ingredient are essential for Ohmic heating of meat. McKenna et al. (2006) prepared pork cuts by sectioning the entire specimen of lean cuts in the direction of the muscle fibers, which could reduce the possible variation in the EC of the pork samples due to the orientation of fibers. EC of different commodities have been reported by several researchers: goat meat (Saif et al., 2004), chicken (Mitchell and de Alwis, 1989; Palaniappan and Sastry, 1991a; Sarang et al., 2008; Tulsiyan et al., 2008), beef (Palaniappan and Sastry, 1991a; Kim et al., 1996; Sarang et al., 2008), and pork (Halden et al., 1990; Shirsat et al., 2004b; Sarang et al., 2008).

It has reported in the literature that during heating of the food materials, cell rupture, tissue shrinkage, changes in membrane permeability, phase changes, dehydration, starch gelatinization, and so on, occur (Palaniappan and Sastry, 1991a,b). Consequently, EC could be affected by these changes as the temperature increased. Considering that the Ohmic heating is based on the resistance of the materials; the EC of the solid foods becomes a critical parameter when processing foods by Ohmic heating. Furthermore, solid foods contain different components (such as protein, fat, fiber, etc.) with different electrical resistance that can affect the overall EC of the food.

3.2.3 CONDUCTIVITY OF MULTICOMPONENT FOOD MATRIX

The real food system usually contains both liquid and solid particles. The solid phase could be small particles such as pulp in fruit juices or larger particles such as carrot, potato, or meat particles in soup formula. Researchers following earlier studies for liquid food containing soluble solid or small particles, and solid food materials continued EC measurements for food commodities. Recently, researchers have been keen to investigate the heating behavior and EC of more complex multiphase food systems containing larger particles (20–30 mm in size) of different commodities such as vegetables and meat, as the solid phase, immersed in a carrier aqueous fluid as the liquid phase. Food industries have also slowly shown their interest in the application of Ohmic heating technology in the processing of particulate foods. It is well known that it is the overall resistance of food material that controls the heating rate under Ohmic heating conditions. Heating rates should be known in order to ensure the proper design of the process from a product safety and quality point of view.

The presence of different materials, volume of each component, size and shape as well as the residence time distribution of solids in a continuous tube-flow processing are among the important factors that affect the overall EC of a multiphase food system. In aseptic processing of two-phase food systems, Ohmic heating of food products is seen as a potential alternative to conventional heating processes because particles could heat faster than liquids, depending on the EC of the solid and liquid phase.

Sastry and Salengke (1998) compared Ohmic heating of solid–liquid mixtures using available mathematical models (Sastry, 1992; Zhang and Fryer, 1993) under worst-case heating conditions. They reported identical results using different models under situations where solid and fluid EC were equal. However, when the solid was of lower EC than the fluid, the circuit analogy mixed fluid (CAMF) approach was shown to be more conservative than the Laplace equation no convection (LENC) approach. If the solid was more conductive than the fluid, the LENC approach was more conservative than the CAMF approach. Their experimental studies confirmed that the worst-case scenario in Ohmic heating was not necessarily associated with a stationary fluid situation. The worst-case situation involving low EC solids appeared to be more likely in their analysis and less avoidable than the situation involving high EC solids. Davies et al. (1999) noted that homogeneity in the heating rate is crucial to ensuring uniformity of local heating rate. They showed that the presence of any electrical insulator within the system would create a region in which heating rates are different. Therefore, care must be taken when preparing formulas for Ohmic heating processes. Benabderrahmane and Pain (2000) developed a model simulating thermal behavior of a solid–liquid system and demonstrated the influence of inhomogeneous EC on heating of material.

In a real food matrix, not only the overall EC of the product but also the EC of each individual component plays an important rule in the heating rate of the product. The EC of each element determines how uniform the product can be heated. Therefore, the heating behavior of individual components could not be described by the measurement of a total effective product EC. Nonuniformity in a product results in a variation in the heating rate where components with significantly different EC exist. Despite the data available about the EC of some solid and liquid foods, little work has been done in comparing the EC of individual components in a multicomponent food product. This shows the importance of studying the EC of each main ingredient of a food matrix. In practice, most vegetable solid particles exhibit lower electrical conductivities than liquids. Soaking treatments have

been proposed in some studies (Palaniappan and Sastry, 1991a; Wang and Sastry, 1993), to increase the electrolytic content of solid pieces of food in order to match electrical conductivities of the liquid and solid phase of particulate foods for the best efficiency of the Ohmic heating process.

Zareifard et al. (2003) experimented with the Ohmic heating behavior and EC of two-phase food systems comprised of a liquid phase using 4% w/w starch solution with 0.5% w/w salt, and a solid phase containing carrot puree and cubes of different sizes (6 and 13 mm) in different concentrations (0–60% w/w). Ohmic heating was applied to the food systems using a static cell (20-mm-long Teflon cylinder with a 35-mm diameter and 25-mm wall thickness) at a constant voltage gradient of 12.5 V/cm. EC values were calculated as a function of particle size, concentration, and temperature. They observed that the heating time increased along with particle size and concentration. Overall values of the EC ranged from 0.2 to 1.8 S/m, increasing with the process temperature as it ranged from 20°C to 80°C, and decreasing as particle size or concentration increased.

Recently, Tulsian et al. (2008) evaluated a real multicomponent food system under Ohmic heating conditions. The objectives of their study were to develop a device for EC measurement extending up to a temperature of 140°C during Ohmic heating; and to measure and compare the EC of the individual components of the chicken chow mein (a food ration of the US Army) over the sterilization temperature range (mentioned elsewhere). The system was capable of operation at above atmospheric pressure, so that EC could be measured at sterilization temperatures. The product composed of chicken, celery, mushrooms, water chestnuts, bean sprouts, and chow-mein-style sauce. They reported that the sauce was much more conductive than the solid particles (vegetables and chicken). High EC of chow-mein-style sauce is related to the existence of salt and soy, ingredients that are highly conducted. More importantly, they noticed some variation in EC between different samples of the same component, which could be justified by the variation in fat content of individual samples.

3.3 EC MEASUREMENT METHODS

EC is one of the properties of material along with other properties such as thermal conductivity and diffusivity, which controls the Ohmic heating behavior. The theory of EC measurements is not complicated and is easy to evaluate as long as the voltage applied and the current passing through the material of interest can be monitored and recorded. The same procedure is followed for both biological and engineering materials to determine the EC, but of course different methods and techniques have been developed for each concept. This parameter is temperature dependent and specifically in case of biological material, due to its complexity (usually multi component, multi phase, and non-homogenous) there are many other parameters that can affect the EC measurement and make it more difficult to perform.

Food materials have been reported to have a wide range of electrical conductivities from 10^{-3} to about 10^2 S/m (Stirling, 1987; de Alwis et al., 1989), between conducting materials and insulators. In an Ohmic heating system, EC (σ) can be determined from the resistance of the sample and the geometry of the cell using the following equation (Palaniappan and Sastry, 1991a,b):

$$s = \left(\frac{1}{R} \right) \left(\frac{L}{A} \right) \times 100$$

where L is the distance between the electrodes (cm) and A is the cross-section surface area of the electrodes (cm²). The resistance of the sample (R) in ohms can be calculated from voltage (V) and current (I) data as $R = V/I$.

Devices have been developed to measure electrical conductivities of solid food pieces for various geometries (Mizrahi et al., 1975; Mitchell and de Alwis, 1989; Palaniappan and Sastry, 1991a; Marcotte, 1999; Tulsian et al., 2008), as it was not easy to find commercial meters that would give results at the frequency generally encountered during Ohmic heating. In its simplest form, this

measurement involves the determination of the resistance of the sample between two electrodes of a fixed shape at a given distance. The ratio of L/A is usually defined as the cell constant which could vary from 1 to 50 cm^{-1} (Cummings and Torrance, 1985). Usually, the current is measured when a fixed voltage is applied. The exact geometry of the sample must be known. A ratio of the distance to diameter of four was found to give reproducible results for food materials (Mitchell and de Alwis, 1989).

Electrical conductivities of liquids are usually calculated from the resistance and the geometry of the measurement cells. The resistance is obtained from the voltage and the current. Since transformers and other electrical equipment have limitations on current, an optimal geometric configuration must be designed to achieve the desired EC at practical voltage levels. Therefore, to best utilize the available power, the EC of the product has to be carefully evaluated in the design.

Practical measurements of liquid electrical conductivities are commonly performed with commercial meters, which operate at frequencies at or above 1 kHz (Mitchell and de Alwis, 1989; Halden et al., 1990; Marcotte et al., 1998). Yet, for fluids with a high concentration of dissolved ions, it has been reported that the EC is a strong function of the frequency (Falkenhagen, 1934; Imai et al., 1995). To avoid polarization in cells and capacitive errors in measurements, the establishment of the frequency selection in meters is essential.

The relationship between the EC of the liquid and the resistance across the electrodes includes a cell constant (i.e., ratio of distance between electrodes to area of electrodes L/A). It is a common practice to maintain the resistance between limits of 10 and 100,000 Ω . Most food liquids would necessitate a practical cell constant of 50 cm^{-1} (Jones, 1897). To measure the conductivity accurately, it is necessary to determine the cell constant. While it is possible to measure the geometry of the cell if it is large enough, the usual practice is to measure the resistance when the cell is filled with a solution whose EC is accurately known. For reference purposes, aqueous solutions of potassium chloride are normally used. Crow (1979) reported that for high conductivities, high cell constants would be used to increase the sensitivity of the measurement (i.e., small electrodes and large distances between electrodes). For small conductivities, the ratio L/A should be very small. Therefore, large electrodes will be used and the length between electrodes will be short. Several authors (Crow, 1979; de Alwis et al., 1989; Palaniappan and Sastry, 1991b; Yongsawatdigul et al., 1995) have reported that there is no voltage gradient effect on electrical conductivities of liquids.

Another important factor to control is the extent of polarization during the measurement. This depends on several factors such as the nature of the electrode surface and the frequency of the alternating current. The restrictions arising from the electrode surface impose a choice on the material. Normally, treated or coated electrodes are used, provided that the frequency is in the range normally found in commercial instruments (50–1000 Hz). Increasing the frequency of the applied voltage can reduce polarization. The effect of frequency is particularly important for the range of measured electrical conductivities for foods (Cummings and Torrance, 1985).

Electrical conductivities are usually measured at room temperature which is not the only temperature experienced by food during Ohmic heating. Therefore, it is important to quantify electrical conductivities at different temperatures because many researchers have reported that with a temperature increase EC also increases (Halden et al., 1990; Fryer et al., 1993; Yongsawatdigul et al., 1995; Wang and Sastry, 1997; Marcotte et al., 1998; Roberts et al., 1998; Zareifard et al., 2003). Early EC measurements were investigated as a quality control tool to evaluate physiological processes occurring during growth in plant tissues (Bean et al., 1960; Weaver and Jackson, 1966; Sasson and Monselise, 1977). Later on, Wang and Sastry (1997) reported that temperature has significant effect on the EC of foods in the Ohmic heating process.

The measurement of EC for food material has been carried out by groups of researchers using different approaches. Most investigators have used either the static or batch Ohmic cell, while only a few have employed continuous units in their study. Different techniques such as variable frequency and voltage gradient were used in order to evaluate the EC under different conditions using either batch or continuous Ohmic heating unit operation systems. Some of these techniques and findings will be explained in greater detail in the following sections.

3.3.1 BATCH OHMIC HEATING SYSTEM

A schematic of the static Ohmic heating cell is presented in Figure 3.2. A typical system contains a cylindrical cell of different length and diameter with two electrodes installed at the ends, a power supply unit, thermometers, data logger, and a computer. Many researchers have tried to develop static Ohmic units that contain an EC measurement device. After early studies on Ohmic heating in the early 1990s and a considerable research gap in application of the Ohmic heating process in food material, Mitchell and de Alwis (1989) developed an EC meter for food samples only at room temperature. Following that, a cylindrical static Ohmic unit was constructed by Palaniappan and Sastry (1991a) using a steel tube (31.7 cm in length and 2.4 cm in diameter, cell constant of $L/A = 7 \text{ cm}^{-1}$) with a Teflon sleeve inside it. A thermocouple opening was placed at the center of the unit and rhodium-plated stainless-steel electrodes at both ends. The system was capable of measuring the temperature at the geometric center of the sample using a T-type copper-constantan, Teflon-coated thermocouple. The voltage and current through the samples were measured. A computer-controlled system (Rosemount) was used to maintain constant voltage during heating. The system could be operated with an alternating current of 60 V and 60 Hz. Palaniappan and Sastry (1991b) set the unit to study the effect of solid content on the EC of tomato and orange juices. In general, tomato juice had higher conductivities compared to orange juice, regardless of the solid content and different temperature. They found that the temperature had a linear increasing effect in conductivities of juices whereas the solids content had a decreasing effect on the EC. Considering that there was no salt in the tomato juice and it had a higher pH, they concluded that orange juice conductivity might be affected by nonionic substance like oil and sugars. Furthermore, with the increase of equal amount of solids, the decrease in the EC of orange juice was lower than for tomato juice. In another study, Palaniappan and Sastry (1991a) used the same unit to measure the electrical conductivities of solid foods such as potato, carrot, and yam samples untreated and after being soaked in water and various salt solutions (0.2%, 0.4%, 0.8%) until saturated. All vegetable samples saturated with water had lower electrical conductivities than the control. Infusion of salt increased electrical conductivities, with the extent of increase dependent on salt concentration.

Another static Ohmic heating cell (which was more appropriate for food materials due to the lower cell constant value ($L/A = 1.14 \text{ cm}^{-1}$) compared to the unit of Palaniappan and Sastry, 1991a) was developed by Marcotte (1999). This unit comprised of a glass cylinder 5 cm in diameter where a sample volume could be introduced between two titanium electrodes. The cross-sectional surface area of electrodes was 18.1 cm^2 , with a gap of 20.69 cm between the electrodes. Voltage and AC current were supplied and controlled by a power unit that included a variable transformer, an isolation transformer, a voltage transducer, a current transducer, power relays and fuses. One

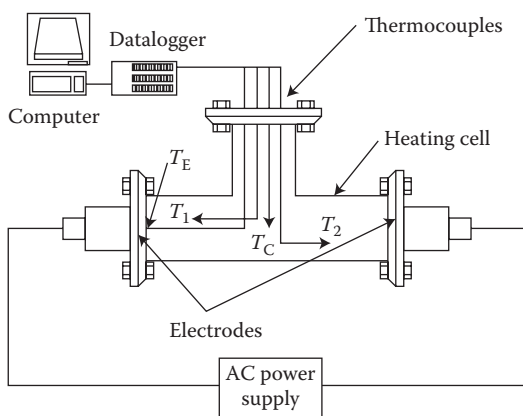


FIGURE 3.2 Schematic of the typical static Ohmic heating cell.

T-Type thermocouple, coated with Teflon to prevent interference with the electrical field, was fitted at the geometric center of the cylinder. Thermal lags due to Teflon coating of the thermocouple were corrected using data from preliminary calibration experiments involving comparison with a certified mercury-in-glass thermometer and uncoated thermocouple junctions under conventional heating conditions. The thermocouple was checked for its accuracy against a certified mercury-in-glass thermometer (National Research Council NRC #1598, Canada) for a temperature range of 20–100°C. In addition, their response time was evaluated by immersing them from 20°C to 100°C in a temperature-controlled silicone oil agitated bath. During the experiment, time, temperature, voltage, and current data could be recorded at selected intervals using a datalogger (Fluke Hydra 2520, Fluke Corporation, Everett, WA) connected to a computer, and measured values of voltage and current could be used to calculate the EC. To measure the EC, a similar static Ohmic heating cell unit was developed by Zareifard et al. (2003) using a Teflon cylinder with a 2.54 cm thick wall and internal diameter of 7.0 cm, resulting in an even lower cell constant value as $L/A = 0.4$. The distance between electrodes was 20 cm, which were connected to the power unit. The unit was operated with a constant voltage of 250 V and the maximum current of 10 A. Voltage and current were recorded during heating and used to calculate EC.

Using a polyvinyl chloride (PVC) pipe (of 5 cm long and 2.65 cm (i.d.) diameter), Shirsat et al. (2004a) constructed a conductivity cell with a cell constant (L/A) of 0.97. The cell was sealed at the ends of the tube and had an opening in the center of the tube where a thermocouple can be placed for measuring temperature. Furthermore, voltage and current were also monitored. The cell was calibrated using different concentration of potassium chloride solutions (Analar, BDH Chemicals Ltd., Poole, UK) as reference standards and validated using different concentration of sodium chloride solutions (Merck KGaA, 64271 Darmstadt, Germany). To measure meat EC, cylindrical samples were prepared and placed in the cell in such a way that the muscle fibers were positioned parallel to the electric field. This was done to prevent the muscle fiber orientation effect on the conductivity, whereas with respect to the electrical field, it has been reported that the particle orientation has a significant effect on the conductivities of solids (de Alwis and Fryer, 1990; Sastry and Palaniappan, 1992). However, minced lean and fat samples were packed into the conductivity cell and tapped with a metal plunger to prevent the formation of air pockets.

Marcotte (1999) compared different static cells to investigate the effect of distance between electrodes and cross-sectional surface area of electrodes which affect EC, temperature profiles, and heating rates during Ohmic heating. Table 3.1 summarizes the geometries of different used cells. They concluded that the length had a strong effect on time–temperature profiles whereas the effect of surface area was negligible.

To measure the EC of solid food particles (celery, chestnut, chicken, and blanched mushroom) in an Ohmic heating system, a device was developed and tested by Tulsian et al. (2008). The schematic

TABLE 3.1
Geometrical Dimensions of Teflon Cells

Teflon Cell	Distance (cm)	Electrode Surface Area (cm ²)	Volume (cm ³)
Short	10.05	19.85	200
Medium	14.33	19.85	285
Large	20.00	19.85	400
Short	10.05	37.97	380
Medium	14.33	37.97	545
Large	20.00	37.97	760

Source: Adapted from Marcotte, M. 1999. Ohmic Heating of Viscous Liquid Foods. PhD thesis, Department of Food Science and Agricultural Chemistry, McGill University, Canada.

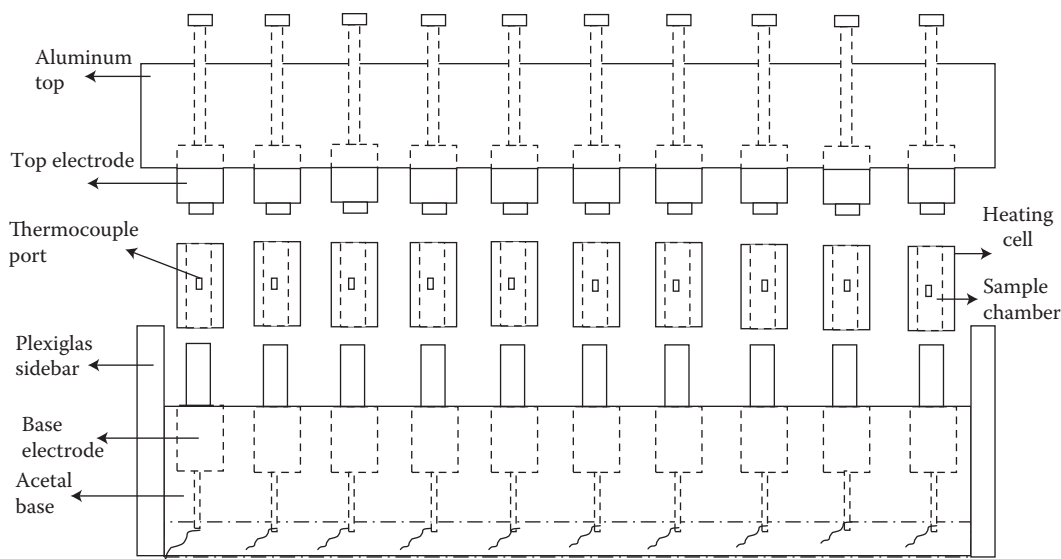


FIGURE 3.3 Schematic view of an Ohmic heating device. (Adapted from Tulsian, P., Sarang, S., and Sastry, S.K. 2008. *International Journal of Food Properties* 11:233–241.)

diagram of the device used is shown in Figure 3.3, in which a base was constructed from Acetal that can house 10 electrodes made from titanium with platinum coat. The device top was made from aluminum, which also can incorporate ten electrodes. These cells had a cylindrical sample chamber through their center that could be fitted over the base electrodes using O-rings. The system was equipped with a thermocouple (Cleveland Electric Laboratories, Twinsburg, OH) to measure temperature (Ohio Semitronics, Hilliard, OH) as well as transducers to measure the voltage and current (Keithley Instruments Inc., Cleveland, OH) flowing through the samples. To measure the EC at sterilization temperatures, the system was made in a way that could be operated at above atmospheric pressure. In such a system 10 samples could be tested and their results could be compared at the same time. The food samples were then sandwiched between the base and the top electrodes. The Ohmic cells were connected to a relay switch that directed the order in which the cells were heated.

3.3.2 A CONTINUOUS OHMIC HEATING SYSTEM

The benefits of Ohmic heating in a continuous food processing system are numerous (Biss et al., 1989). The most important is that heating is very rapid and a large temperature gradient is not experienced within the food, that is, heating is uniform. Ohmic heating has the ability to heat the food continuously without the need of the hot heat-transfer surface of a scraped surface heat exchanger (SSHE) or a tubular heat exchanger that may foul. Using an Ohmic heater, particles are handled more gently and maintain their integrity when compared with a SSHE. The process is a quiet operation due to the absence of rotating parts in the system. In addition, a high percentage of solids in liquid (50–80%) can be processed. Unlike microwave heating, the depth of heat penetration in the food is virtually unlimited. A high level of control and automation ensures safety during the operation. Finally, it is easier to tailor a heating time–temperature profile to ensure sterility because heat is generated within the solids without the reliance on thermal conductivity through the liquid.

The Ohmic heater assembly can be seen in the context of a complete product sterilization or cooking process where there is already a holding tube, pumping and a cooling system. The Ohmic heater replaces the SSHE in an aseptic processing line, as shown in Figure 3.4. In this case, an Ohmic heating column consisting of four electrodes would replace the conventional SSHE. The food product is

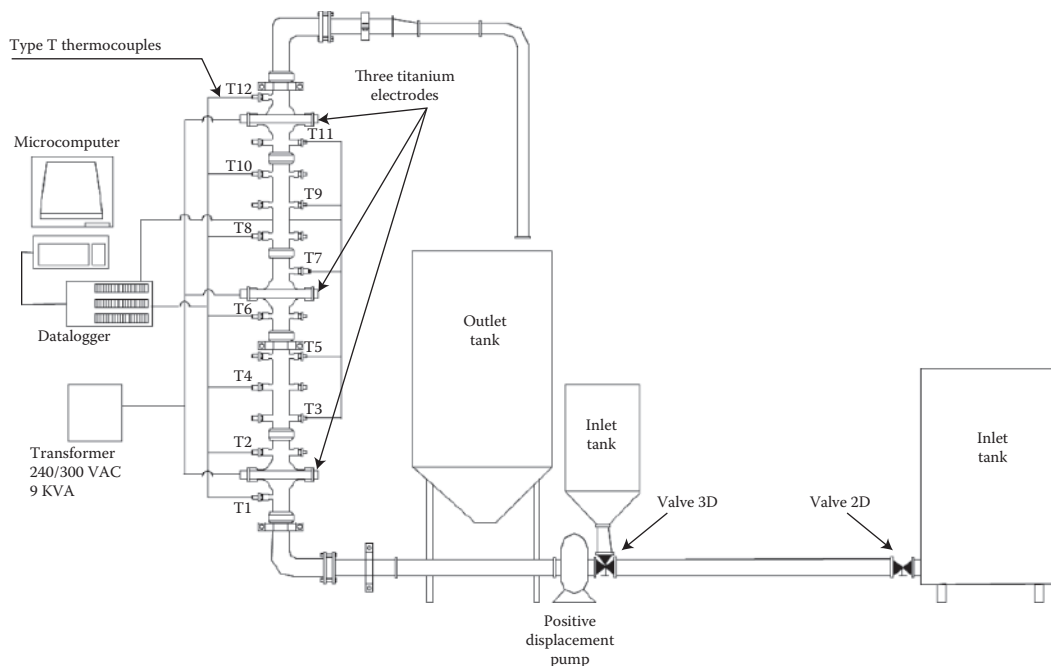


FIGURE 3.4 Basic design and main components of a continuous Ohmic heating system.

fed vertically from the bottom to the top of the column. Heating occurs in three sections between two electrodes. The food is then held in the holding tube for temperature equilibration between the liquid and solid. It is cooled in tubular heat exchangers before being packed in an aseptic environment. Commercial APV Ohmic heating installations are available for different production throughput. As an example, a 30 kW unit is needed to process up to 300 kg/h and 75, 125, 300, and 600 kW units are used for 750, 1250, 3000, and 6000 kg/h of product, respectively. For laboratory experiments, a 5 kW unit is used for a single batch of 50 kg or it can be operated in a continuous mode of 50 kg/h. The power for pilot scale units is 10 kW for a continuous production of 100 kg/h. This particular Ohmic heating technology for particulate foods was first developed by the Electrical Council Research in Capenhurst, England. It was licensed to APV Baker Ltd for commercial exploitation of the results. APV has patented the electrode assembly in England (Simpson, 1980) and in the United States (Simpson, 1983). Over 18 commercial industrial plants were installed, mostly in Europe and Japan and more recently in the United States. Several authors (Taffe, 1987; Frampton, 1988; Swientek, 1988; Grikitis, 1989; Sperber, 1992; Anon., 1994; Pain et al., 1995; Rice, 1995; Tjomb, 1995; Anon., 1996) have reported on the commercial application of the APV Ohmic heating technology for particulate foods. Tables 3.2 and 3.3 summarize the information and illustrate some examples of commercial Ohmic heating units used for laboratory, pilot, and industrial applications with food systems.

Continuous Ohmic heating systems have been commercially used for continuous processing of food materials (Stirling, 1987; Skudder, 1991). However, EC values for process design were mainly obtained from the data bank of static approach. In recent years, attempts have been made to design and fabricate pilot scale continuous Ohmic heating systems for processing of foods (Mälkki and Jussila, 1979; Stirling, 1987; Skudder, 1991; Qihua et al., 1993; Marcotte et al., 2000) in order to have a better understanding of the heating behavior and more realistic data on EC of food materials undergoing Ohmic process.

Qihua et al. (1993) designed and constructed a continuous-flow Ohmic heating unit, using an acrylic cylinder, 6 cm in diameter and 30.48 cm long. The stainless-steel electrodes were tightly positioned at each end of the cylinder using rubber rings and acrylic cover plates tightened with nuts and

TABLE 3.2
Commercial Development and Implementation of the Ohmic Heating Technology for Fluids Containing Particulates

Date	Events
1980	UK patent for electrode assembly to Electrical Council Research at Capenhurst (ECRC) in UK
1983	US Patent for electrode assembly to ECRC
1983	Exclusive international exploitation license given to APV from ECRC
1988	Food Processing Award in UK
1989	Start-up of the first industrial unit in UK
1990	Du-Pont Award in US
	Du-Pont Diamond Award in US
1991	Power for Efficiency and Productivity Price in UK
1991	Eta Price from International Union of Producers and Distributors of Electrical Energy
1991	Approval of APV Ohmic heating technology for the production of ambient stable low acid ready meals in the UK
1992	First US based Ohmic-aseptic system installed at the Advanced Food Science (AFS) at Land O'Lakes
1993	FDA in the United States approved the Ohmic heating technology for low acid fluids containing particulates
1993	Royal Society Esso Energy for the best energy utilisation
1995	Approval of the APV Ohmic heating technology for the production of high acid fruit products for institutional use in the UK
1996	APV received the Industry Achievement Award from IFT
1996–2012	High frequency power supply systems have been developed by EMMEPIEMME, APV and others for several industrial applications

Source: Adapted from Marcotte, M. 1999. Ohmic Heating of Viscous Liquid Foods. PhD thesis, Department of Food Science and Agricultural Chemistry, McGill University, Canada.

bolts. The unit could be placed horizontally or vertically. Temperature distribution was monitored by nine T-type (copper-constantan) thermocouples installed along the axial and radial positions. The flow control system of the unit consisted of a pump (with a maximum flow rate of 10 L/min and 1.4 m head), connecting tubes, T-joints and valves. The unit equipped with a data-acquisition system for monitoring the temperature distribution, applied voltage, and current with time.

Marcotte et al. (2000) designed and fabricated a pilot plant continuous Ohmic heating unit to study the heating profile of liquid foods undergoing an Ohmic heating process. The Ohmic heating mechanism was a collinear heater similar to the APV Ohmic heater for particulate liquid foods. The electric field distribution was parallel to the flow of product. The continuous Ohmic heating unit was assembled from two basic units: three electrode housings and two spacer tubes or heating sections. The electrodes were made from titanium. All internal surfaces in contact with the food are constructed from insulating glass material except for the electrodes. The internal diameter of the glass tube was 5.08 cm. The length of the heating sections, that is, the space between the two first electrodes was 56.2 cm whereas for the other heating section, the length was 56.7 cm. A power unit (Hammond manufacturing, S87853, Guelph, ON, Canada and Bectrol Technologies Inc., St. Hyacinthe, QC, Canada) was used to generate the necessary electrical field at the three electrodes; it included a variable transformer, an isolation transformer, a voltage transducer, a current transducer, power relays, and fuses. A maximum of 900 V for the voltage and 10 A for the current were the physical limits supplied by the power unit. A positive displacement pump (ALBIN Pump SLP-220, Atlanta, GA) was used to flow the food product vertically from the bottom to the top between the electrodes from an inlet tank to an outlet plastic tank. First, the fluid was pumped horizontally on a 3-m length. Then, the fluid was passed through the two vertical Ohmic heating sections (2 m).

TABLE 3.3**Examples of Commercial Ohmic Heating Units for Laboratory, Pilot Scale or Industrial Application**

Who	Year	Where	Power	Product
Sous Chef Ltd (H.J. Heinz division)	1989	UK	75 kW	Prepared meals of meat and vegetables (5, 10, 25 L bulk packaging)
Confidential	NA	Europe	75 kW	High acid products such as fruits in syrup and vegetables and meats
Confidential	NA	Europe	300 kW	Low acid particulate foods
Advanced Food Science (AFS) Land O'Lakes	1992	US, IL	5 kW	R&D assistance for product development, a continuous system
Ohio State Un. NCFST/FDA/APV	1993	US, OH	60 V, 60 Hz	Liquid, solid, and mixture
Bedford Park	1994	US, IL	5 kW	Dynamic batch Ohmic heating unit for research tests
Nissei Co. Wildfruit Division (1 of 6 Ohmic heaters)	NA	Japan	75 kW	High acid particulate foods such as whole strawberries in syrup (10 L units or 10 kg bags in box)
Confidential	NA	Japan	75 kW	Prepared meals
Confidential	NA	Japan	300 kW	High acid particulate foods
Nestlé Food Service Division "Chef Mate brand"	NA	US, MO	300 kW	Shelf stable low acid beef stew and ravioli in # 10 can packaging
CTCPA Dury-lès-Amiens	1995	France	10 kW	Pilot scale installation. Aseptic tank of 150 and 20 L bags in box
UTC Compiègne	1990	France	5 kW	Capacity of 1 kg per batch at a laboratory scale Testing facilities for a full range of products
Odin Packaging Systems, Parma	NA	Italy	NA	NA
EPRI, Palo Alto	1996	US, CA	NA	Liquid, batch, and continuous system
Agriculture Canada Food Res. Center	1999	Canada	5 kW 0–30 kHz	Continuous liquid and solid food
Centro di Tramariglio	2001	Italy	50 kW	Continuous aseptic Ohmic heating system
Sala Baganza, Parme	2002	Mexico	250 kW	NA
Société confidentielle	2003	France	50 kW	Products containing meat

Source: Updated data of Marcotte, M. 1999. Ohmic Heating of Viscous Liquid Foods. PhD thesis, Department of Food Science and Agricultural Chemistry, McGill University, Canada.

On the last part of the horizontal cylinder at the exit of the pipe, the length of the pipe was 55.8 cm. It was followed by a vertical pipe of 68.5 cm to feed the plastic outlet tank. A constant voltage was applied to the three titanium electrodes. Six Teflon-coated type-T thermocouples (Omega Engineering, Stamford, CT) were installed to measure the temperature of carried fluid at the center of the cylinder, and six other thermocouples were also used to determine the temperature of the fluid close to the wall. Temperature, current, and voltage were monitored and recorded at 10 s interval using a data logger (Model 2225, John Fluke MGF Co. Inc., Everett, WA).

To achieve Ohmic heating for liquid food by using rectifier and inverter technology, a continuous Ohmic heating device was designed by Wang et al. (2012). The equipment consisted of a controllable-pulsed power supply, Ohmic heating chamber, pump, and flow controller. A controllable-pulsed power supply can output bipolar-rectangle waveform pulse voltage with high frequency. The frequency, amplitude and duty ratio were adjustable. The output capacity could reach 50 kW. The result of their study showed that the device could be controlled speedily and easily, and meets the requirement of liquid food process.

3.3.3 FREQUENCY VARIATIONS AND CONDUCTIVITY

It has been recognized that in Ohmic heating the heating rate of food materials is dependent on the frequency of alternating current, especially in solid food such as plant tissue, which is made up of individual cell units surrounded by their wall and cell membrane. For example, for fish protein gel (prepared from Alaskan pollack), it was reported that the heating rate at 10 kHz is 7.5 times greater than that at 50 Hz (Park et al., 1995). Considering that the main element of cell membrane is phospholipid that can be referred, electrically, as a condenser. Therefore, the high frequency of alternating current can play an important rule in rapid heating by reducing the impedance of the tissue (Imai et al., 1995).

To measure the EC of liquids, meters operating at frequencies 1 kHz or more are used with properly calibrated probes. Nevertheless, the EC of fluids containing large amount of dissolved or entrapped ions (e.g., foods with high moisture content) may be strongly influenced by frequency (Falkenhagen 1934; Mitchell and de Alwis, 1989). In this regard, it has been reported that a sample of carrot had a conductance of 5×10^{-4} S and 1.1×10^{-2} S when measured at 50 Hz and 50 kHz (Mitchell and de Alwis, 1989).

It has been shown that for fluids with a high concentration of dissolved or entrapped ions, the EC is a strong function of the frequency (Falkenhagen, 1934). For commercial applications, the choice of frequency is usually a compromise between avoiding polarization problems without introducing capacitive errors into the measurements (Mitchell and de Alwis, 1989; Fryer et al., 1993; Kim et al., 1996). Since the frequency effect is important with respect to EC values, it is necessary to measure electrical conductivities in the context of Ohmic heating or at 60 Hz. There is little published information on the electrical properties of foods at low frequencies in the context of Ohmic heating (Mitchell and de Alwis, 1989).

Imai et al. (1995) studied the effect of frequencies (50 Hz to 10 kHz) on the heat generation of Japanese white radish. Of the frequencies examined, 50 Hz gave the sharpest initial rise in temperature and the shortest time to raise the desired temperature. To measure EC of food samples, a multifrequency Ohmic heating system operating at 30 Hz to 1 MHz range was developed by Wu et al. (1998) which could deliver 250 W. The system was tested at frequencies from 55 Hz to 200 kHz with Pacific whiting surimi paste and stabilized mince in the 20–70°C range.

3.3.4 VOLTAGE GRADIENT AND CONDUCTIVITY

Voltage gradient is reported to be another significant variable in Ohmic heating, which has an increasing effect on EC (Palaniappan and Sastry, 1991a; Icier and Ilicali 2004). This increase is mainly due to electro-osmotic effects (Halden et al., 1990; Palaniappan and Sastry, 1991a). It has been shown that the osmotic pressure across a straight capillary media was directly proportional to the voltage gradient (Crow, 1988). The application of voltage causes fluid motion through the capillary porous membranes of the biological tissue. The voltage gradient is reported to be a remarkable variable for different juice concentrations examined by Icier and Ilicali (2004). Therefore, they proposed the following equations for temperature and voltage gradient-dependent EC;

$$\sigma = A1 \cdot (V/\text{cm})^N + A2 \cdot T + A3$$

where σ is the EC, V is the applied voltage, T is the temperature, $A1$, $A2$, $A3$, and N are the empirical constants.

Marcotte (1999) studied the effect of voltage gradient on the heating behavior and EC of four types of hydrocolloids solutions having 0.5% salt, using a Teflon cell at two electrode distances (14.33 and 20.00 cm) and three voltages (100, 250, and 400). Six voltage gradients were obtained: 5.26, 7.14, 13.16, 17.86, 21.05, and 25 V/cm. The results of their study indicated that there was no effect of voltage gradients on EC, but time–temperature profiles were strongly affected by this parameter. Heating rates were found to increase sharply with increasing voltage gradients. Heating rates increased linearly with time and temperature.

Crow (1979) reported that when applying a few volts to electrolytic solutions, there was no measurable variation in EC with voltage gradient. However, at 100 kV/cm, some differences may be observed. Palaniappan and Sastry (1991b) reported no effect of voltage gradient (30–60 V/cm) on the EC of orange juice. Yongsawatdigul et al. (1995) found that a high salt concentration (3–4%) in surimi must exist to observe a voltage gradient effect on EC.

3.3.5 PARTICLE ORIENTATION AND CONDUCTIVITY

It is understood that the particle distribution, concentration, and orientation affect the overall EC of a multicomponent food material (de Alwis and Fryer, 1990; Sastry and Palaniappan, 1992; Zareifard et al., 2003). The location of the solid phase within the Ohmic heating cell in terms of a series or parallel position, or a well-mixed situation with liquid phase, is also another important subject that can affect EC. Since Ohmic heating is based on the passage of an electrical current through the product, knowledge of the electrical conductivities of each phase, as well as the effective conductivity and resistance of the mixture, is essential for appropriate process design. Particle orientation within the electrical field could play a significant role in the heating profile during the Ohmic process. Therefore, to design an Ohmic heating process for a two-phase food system, it is important to know the overall or effective EC as influenced by size, location, and orientation of the particles.

de Alwis and Fryer (1990) developed a mathematical model to study the resistance of a two-phase system in the presence of a single cubic particle under various orientations relative to the current, and the effective resistance of a system consisting of a particle within a cylindrical sample of fluid of different conductivity. The model can be useful in studies of heat transfer during Ohmic heating. Simulations have demonstrated the heating rate of particles to be a function of both particle size and orientation, and of the ratio of solid to liquid's EC. If the solid has a lower EC than the liquid, its under heating problems are most severe. Particle under heating can be avoided by selection of the correct combination of electrical conductivities and particle shape to ensure the maximum amount of thermal conduction.

Sastry and Palaniappan (1992), also studied the effective resistance of a two-phase mixture consisting of liquid and, again, only a single cubic particle in the liquid phase. This showed that the resistance was slightly dependent on orientation. The orientation effect increases as solid-to-liquid conductivity ratio increases, but the effect is not strong. These results were not applicable to the real cases involving higher particles or solid concentration. Situations involving large particle populations were further studied by Zareifard et al. (2003). They conducted experiments and developed method to measure the EC of two-phase food systems as influenced by particle size, concentration, and location of particles while placed in parallel, in series or in well-mixed conditions within the liquid phase. The method was tested and evaluated using a carrot–starch mixture of different particle sizes and solid concentrations. Furthermore, the effect of a solid phase location was also investigated through experiments. For a solid phase location they considered three conditions, where a very thin metal mesh separator was used to keep the solids in place for the first two conditions: (a) solid particles were placed at the bottom of the heating cell, laid horizontally along the wall, and the liquid was added from the top, considered as a parallel condition, (b) solid particles were placed on one side of the Ohmic heating cell in contact with one electrode while the liquid phase was in contact with the other electrode, considered as a series condition, and (c) solid particles were well distributed and mixed with the liquid phase to obtain a well-mixed carrot–starch system. All food systems were heated from room temperature up to 80°C.

3.3.6 HIGH-PRESSURE–HIGH-TEMPERATURE OPERATIONS

A conductance cell that can operate at high temperature and high pressure was designed and built by Quist and Marshall (1968) to measure EC of aqueous sodium chloride solutions, using a cylindrical

bar of Udimet 700 (Special Metals, Inc., New Hartford, NY) with a dimension of 1 in. in diameter and 23.75 in. in length. To house the electrode holder and the high-pressure tubing, a hole was drilled at each end of the bar. The cell was made in such way that, it could operate in continuous mode. The central part of the cell (19 in. long, 0.250 in. i.d., with a mirror-like finish) was coated with a 75% platinum–25% iridium tube (J. Bishop & Co., Malvern, PA) that made it a corrosion-resistant liner and it can also operate as one of the electrodes of the conductance cell. The material used for electrical insulation was polycrystalline AI208 (“Lucalox,” Lamp Glass Department, General Electric Co., Cleveland, OH). The cell was positioned vertically with the electrode holder in the topside of the cell.

To generate a uniform temperature, the resistance heating system had three separate Nichrome windings. Calibrated Pt-10% Rh metal-sheathed thermocouples (inserted along the outside of the cell body) were used to measure the cell temperature. Another calibrated Pt-10% Rh sheathed thermocouple was positioned at several points inside the cell to verify the uniform temperature region and determine the temperature profile along the length of the cell at temperatures to 800°C. The operating pressure was up to 4000 bars. A hand-operated, single-piston pressure generator (High Pressure Equipment Co., Erie, PA) was used to obtain pressures up to 1000 bars. The pressure was measured by a calibrated, Bourdon tube gauge (Heise Bourdon Tube Co., Newtown, CT). However, an air-driven diaphragm pump (Sprague Engineering Corp., Gardena, CA) in conjunction with an intensifier (Hanwood Engineering Co., Inc., Walpole, MA) was used to produce pressures from 1000 to 4000 bars. To measure conductance, the system was equipped with a Wayne Kerr B-211 bridge with an associated audio signal generator (Wayne Kerr Model 5121) and wave-form analyzer (Wayne Kerr Model A321). The system was used to measure the EC of the sodium chloride solution. Their results showed that with the increase of pressure the EC of the solution was increased. However, with the increase of the temperature the EC increased to a certain point (temperature around 350°C) and then it decreased.

3.4 CLOSING REMARKS

Ohmic heating depends, among other factors, highly on the EC of the material. In nonhomogenous materials such as foodstuff, the overall EC of the food depends on the composition, EC of the components as well as their distribution/orientation. EC is one of the important factors to be considered in the design and performance analysis of Ohmic heating. Data are scattered and sometime discrepancies can be observed. Several measurement techniques have been developed to evaluate the EC of food materials for research applications. However, a simple and portable commercial device is still missing for the measurement of the EC of solid and heterogeneous biological material, which could be fast and useful in industrial applications.

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4 The Electrical Conductivity of Foods

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4.1 INTRODUCTION

The design of a continuous Ohmic heating processing line is principally determined by the selected configuration of the system, the heating rate, the flow rate, and the desired temperature rise of the food product (Reznik, 1996). The Ohmic heating rate is calculated from the electric field, electrical conductivity, density, and specific heat of the food product. Therefore, the heating rate depends largely on the physical properties of the food and the electrical conductivity. Ohmic heating works effectively for foods because most pumpable foodstuffs contain dissolved ionic salts and acids, and water in excess of 30%, which render the material electrically conductive (de Alwis and Fryer, 1992). Pure fats, oils, alcohols, and sugars are not suitable materials for Ohmic heating. These substances are not sufficiently electrically conductive. Though, many researchers have worked on the context of Ohmic heating, its application in food processing is not yet fully developed due to the many unknowns in foods undergoing such a heating process. A considerable amount of reliable data on electrical conductivities has been published; however, discrepancies do exist among the available data or the estimates from the proposed empirical models. In some cases, the electrical conductivity of the food materials have been measured at room temperature, which is not the temperature experienced by the food during the Ohmic heating. For proper design of Ohmic heating system, it is essential to measure and collect the electrical conductivity data of foods as well as how they influence parameters such as frequency of the AC voltage applied, the voltage gradient, and the composition of food matrix. Some data has been published for high-frequency processes (e.g., microwave) but they are not applicable to low-frequency Ohmic heating processes. Only a few publications (Fryer et al., 1993; Zareifard et al., 2003; Salengke and Sastry, 2007; Tulsiyan, 2008) have reported electrical conductivities of real food matrices as a mixture of both liquid and solid components. It is generally observed that the electrical conductivity of liquids is higher than that of solids (Sastry and Palaniappan, 1992). In liquid foods, the effect of the proportion of solids is of less importance but still significant. Usually, as the percentage of solids increases (except for salt) the electrical conductivity decreases.

High-energy cost, consumer awareness of the food quality, keen competition in the local and global market, worldwide free business, and considering the use of advanced technology have forced the food industry investors to think seriously and apply the new technologies in order to be on top of the market. Application of Ohmic heating technology in food industries is progressing at a steady rate from European and Japanese countries to the North American market in recent years and a bit slower to the developing countries and other parts of the world. Food machinery manufacturing companies such as APV have designed and manufactured appropriate unit operation systems like Ohmic heating plate heat exchanger for continuous processing of food materials with an affordable price for the industries. The initial Ohmic heating systems have been in commercial operation in the United Kingdom since the early 1990s to process a variety of foods (Parrott, 1992) followed by Japan, France, and the United States. This technology has been used more in liquid foods such as milk and juices. Due to lack of sufficient basic data, such as electrical conductivities of solid food, which are necessary for a high-quality, energy efficient, and safe process design, the technique has not been so commercialized for particulate foods. However, during the last two decades attempts have been made by several researchers to understand the heating behavior and evaluate the electrical conductivity of different food components and matrices. Quite good information is now available, but scattered in literature, and therefore a kind of handbook or a tabulated form of the data is needed. Having provided a short history of the subject, the authors intended to collect the currently available information on the electrical conductivity of different commodities in the literature, and classify them into different categories in the following sections. This helps food processors to apply the Ohmic heating technique for commercial processing of particulate foods and for the researchers to cross check the values and fill up the gaps by developing more accurate equations to predict the electrical conductivities of foods for a given condition in a specific Ohmic heating system.

4.2 ELECTRICAL CONDUCTIVITY DATA FOR AQUEOUS FOODS

Following the initial research work of Fryer's group in England during the late 1980s on Ohmic heating process of food material, Palaniappan and Sastry (1991b) were probably the first to report data on electrical conductivity for liquid foods in the United States. Reporting the experimentally measured values of EC for aqueous foods were followed by other groups, including Kim et al. (1996), Marcotte et al. (1998), Ayadi et al. (2004), McKenna et al. (2006), Legrand et al. (2007), and very recently, Tulsiyan et al. (2008), Kong et al. (2008), and Sun et al. (2008). It is possible to measure the EC of liquids using different probe-type sensors calibrated for a given temperature, mainly at room temperature, and then to make the necessary corrections based on the correction factor provided by sensor manufacturers for higher temperatures. Electrical conductivity values for a variety of liquid foods such as dairy products, fruit juices, and starch-based solutions containing different salt concentrations obtained at room temperature are collected and presented in Table 4.1. In some cases empirical equations were also developed to predict EC at higher temperatures. Not only the temperature, but also other parameters such as solid concentration and particle size were taken into account while measuring the EC of the aqueous solution. For example, different values of EC were reported for tomato and orange juices containing different solids content at different temperatures. Reducing the particle size of juice solids increases the effective conductivity of the juice (Palaniappan and Sastry, 1991b).

Marcotte et al. (1998) measured the electrical conductivity of five hydrocolloids solutions of different concentrations at various temperatures, and developed mathematical models in order to predict the EC of such solutions. Among the examined hydrocolloids, the highest values of EC were reported for 1% carrageenan (0.2s/m), followed by 1% xanthan (0.14s/m) at 25°C. Pectin and gelatin samples were found to demonstrate lower, and the lowest value was obtained from 4% starch samples (0.05s/m) at room temperature. In another study, Marcotte et al. (2000) determined the electrical conductivity of selected hydrocolloids with various salt concentrations (0.25%, 0.50%,

TABLE 4.1
Published Electrical Conductivities of Various Liquid Foods at Room Temperature (20–25°C)

Food Material	EC (S/m)	References
Tomato juice	0.863	Palaniappan and Sastry (1991b)
Orange juice	0.567	Palaniappan and Sastry (1991b)
Starch solution (5.5%) including		
0.2% salt	0.34	
0.55% salt	1.3	Kim et al. (1996)
2% salt	4.3	
Carrageenan		Marcotte et al. (1998)
1%	0.206	
2%	0.390	
3%	0.470	
Xanthan		Marcotte et al. (1998)
1%	0.139	
2%	0.250	
3%	0.400	
Gelatin		Marcotte et al. (1998)
2%	0.062	
3%	0.089	
4%	0.110	
Pectin		Marcotte et al. (1998)
1%	0.047	
3%	0.101	
5%	0.140	
Starch		Marcotte et al. (1998)
4%	0.051	
5%	0.057	
6%	0.069	
Carrageenan (1.7%)		Marcotte et al. (2000)
Salt concentration (%)		
0.25	0.848	
0.50	1.371	
0.75	1.914	
1.00	2.173	
Xanthan (2%)		Marcotte et al. (2000)
Salt concentration (%)		
0.25	0.889	
0.50	1.474	
0.75	1.969	
1.00	2.162	
Pectin (2.5%)		Marcotte et al. (2000)
Salt concentration (%)		
0.25	0.691	
0.50	1.201	
0.75	1.690	
1.00	2.195	
Starch (4.3%)		Marcotte et al. (2000)
Salt concentration (%)		
0.25	0.582	

continued

TABLE 4.1 (continued)**Published Electrical Conductivities of Various Liquid Foods at Room Temperature (20–25°C)**

Food Material	EC (S/m)	References
0.50	1.066	
0.75	1.544	
1.00	2.109	
B-Lactoglobulin solution (1 wt%)	0.155	Ayadi et al. (2004)
β -Lactoglobulin–xanthan mixture solution (1 wt% protein + 0.2 wt% xanthan gum)	0.156	Ayadi et al. (2004)
Deposit from Ohmic heating of β -lactoglobulin solution (1 wt%)	0.058	Ayadi et al. (2004)
Deposit from Ohmic heating of β -lactoglobulin–xanthan mixture (1 wt% protein + 0.2 wt% xanthan gum)	0.090	Ayadi et al. (2004)
Tap water	0.058	Kong et al. (2008)
Fruit–vegetable juice	0.191	Kong et al. (2008)
Yogurt	0.609	Kong et al. (2008)
0.5% aqueous NaCl solution	0.992	Kong et al. (2008)
Milk (raw and commercial)	0.390	Sun et al. (2008)
(low fat)	0.420	
NaCl		
0.02 (mol L ⁻¹)	0.24	McKenna et al. (2006)
0.05 (mol L ⁻¹)	0.56	
0.17 (mol L ⁻¹)	1.79	

Note: Values of Kim et al. (1996) were measured at 19°C. Values of McKenna et al. (2006) and Sun et al. (2008) were measured at 20°C, all other values at 25°C.

0.75%, and 1.0%) and citric acid addition (normal and modified pH). They reported that the higher EC values were associated with the samples that had higher salt concentration. However, the effect was more evident at higher temperatures.

Ruhlman et al. (2001) measured the EC of various liquid foods at refrigerated and room temperature as well as four other given temperatures up to 60°C. These values are presented in Table 4.2. Their results revealed that among the product measured, vegetable juice samples showed the highest overall electrical conductivity, and the lowest electrical conductivity belonged to beer samples. They concluded that the greater electrical conductivity of vegetable juice might be a result from the presence of salt in the formulation. Furthermore, the greatest variability was found in the fruit juice group (79%), whereas the lowest variability was found in the milk group products (21%). They related the large variation of the electrical conductivity in the fruit juice products to the difference in their physical properties and ionic make up of the original fruits.

Protein–polysaccharide mixtures are the most commonly used materials for improvement of the structure, texture, and stability of many foodstuffs. To investigate the electrical conductivity of such solution using xanthan gum and whey protein powder, Ayadi et al. (2004) conducted experiments to determine the EC of prepared fouling model fluids (aqueous solution of ultra-pure β -lactoglobulin of different concentrations 1, 2.5, 5, 7.5, and 10 g/L) at neutral pH within a temperature range of 10–100°C. As expected, their results indicated higher electrical conductivity was obtained at higher temperatures. However, some discrepancies between the electrical conductivity of the solutions were also reported, which were related to the structural differences between protein and xanthan gum molecules and their interaction.

TABLE 4.2
Published Electrical Conductivities (S/m) of Liquid Foods at Different Temperatures

Product	Temperature (in °C)					
	4	22	30	40	50	60
Beer	0.080	0.143	0.160	0.188	0.227	0.257
Light beer	0.083	0.122	0.143	0.167	0.193	0.218
Black coffee	0.138	0.182	0.207	0.237	0.275	0.312
Coffee with milk	0.265	0.357	0.402	0.470	0.550	0.633
Coffee with sugar	0.133	0.185	0.210	0.250	0.287	0.323
Apple juice	0.196	0.239	0.279	0.333	0.383	0.439
Cranberry juice	0.063	0.090	0.105	0.123	0.148	0.171
Grape juice	0.056	0.083	0.092	0.104	0.122	0.144
Lemonade	0.084	0.123	0.143	0.172	0.199	0.227
Limeade	0.090	0.117	0.137	0.163	0.188	0.217
Orange juice	0.314	0.360	0.429	0.500	0.600	0.690
Carrot juice	0.788	1.147	1.282	1.484	1.741	1.980
Tomato juice	1.190	1.697	1.974	2.371	2.754	3.140
Vegetable juice cocktail	1.087	1.556	1.812	2.141	2.520	2.828
Chocolate milk (3% fat)	0.332	0.433	0.483	0.567	0.700	0.800
Chocolate milk (2% fat)	0.420	0.508	0.617	0.700	0.833	1.000
Chocolate skim milk	0.532	0.558	0.663	0.746	0.948	1.089
Lactose-free milk	0.380	0.497	0.583	0.717	0.817	0.883
Skim milk	0.328	0.511	0.599	0.713	0.832	0.973
Whole milk	0.357	0.527	0.617	0.683	0.800	0.883

Source: Data from Ruhlman, K.T., Jin, Z.T., and Zhang, Q.H. 2001. Chapter 3 in *Pulsed Electric Fields in Food Processing*. G.V. Barbosa-Canovas and Q.H. Zhang, Eds. Technomic Publishing Co., Lancaster, PA, pp. 45–56.

Legrand et al. (2007) measured the EC of carrier fluid (0.8% w/w xanthan gum, 1.5% w/w NaCl salt, and 97.7% w/w water) containing different concentration of blanched beans. They found that higher values of EC were associated with high temperature and, in regard to particle concentration, lower values of EC were obtained at higher concentration.

Conducting Ohmic heating experiments on different liquid samples (tap water, fruit vegetable juice, yogurt, and 0.5% aqueous NaCl solution), Kong et al. (2008) reported an increase in the EC of the tested liquid samples up to a critical temperature of 50–60°C, thereafter the rate decreased. They concluded that the decrease in EC might be due to the water loss that is caused by the amount of heat generated at higher temperature. Tulsiyan et al. (2008) reported values of EC for individual components and a multicomponent food system named *chow mein* (chicken, celery, mushrooms, water chestnuts, bean sprouts, and *chow mein*-style sauce) over a temperature range of 25–140°C. Their results indicated that the sauce had a higher conductivity (2.1s/m at 27°C to 10.8 S/m at 140°C) than the solid components.

4.3 ELECTRICAL CONDUCTIVITY DATA FOR PASTY MATERIALS AND MEAT PRODUCTS

There are only a few studies available in the early 1990s concerning evaluation of EC for meat products (Mitchell and de Alwis, 1989; Halden et al., 1990; Palaniappan and Sastry, 1991a; Yongsawatdigul et al., 1995) along with the initial works on the EC of liquid foods. However, in recent years, more attempts (Wu et al., 1998; Shirsat et al., 2004b; McKenna et al., 2006; Pongviratchai and Park, 2007; Sarang et al., 2008; Tulsiyan et al., 2008) have been made to measure

the EC of meat and pasty material due to the rapid increase of Ohmic heating application in the processing of real food matrices including meaty component. Available data on the EC of meat pieces (chicken, beef, fish, and pork) and some meat formulations at a given temperature are presented in Tables 4.3 and 4.4. Food processing sometimes starts with defrosting of frozen meat products. Less research was conducted at lower temperatures to determine the EC of frozen foodstuffs, while knowledge of EC of different fishes and meats at lower temperature is essential since the Ohmic heating process could also be applicable in defrosting process of the frozen food.

Yongsawatdigul et al. (1995) determined EC of fish paste (Pacific whiting surimi) contained various moisture (75%, 78%, 81%, and 84%) and salt contents (1%, 2%, 3%, and 4%). They found that the electrical conductivity of surimi paste containing salt were higher at elevated temperatures. Moreover, they also reported that the electrical conductivity had a linear relationship with temperature.

Pongviratchai and Park (2007) conducted a study to determine the electrical conductivity of surimi–starch paste prepared from Alaska pollock. The surimi was mixed with native and pregelated potato starch at different concentrations (0%, 3%, and 9%), with 2% salt at two different moisture contents (75% and 81%) using a multifrequency Ohmic heating system. Three different frequencies (55 Hz, 5 kHz, and 20 kHz) at alternating currents of 4.3 and 15.5 V/cm voltage gradient were tested in this study. Their results showed that higher electrical conductivity values were obtained with high moisture content, applied frequency, and applied voltage. However, lower values of electrical conductivity were associated with the high starch concentration.

Although a certain amount of information exists on the conductivity of whole meats, little information is available on the electrical conductivity of meat batters or multi-component meat products, like most of the processed foods.

Some studies were conducted to determine the electrical conductivity of meaty products (Yongsawatdigul et al., 1995; Shirsat et al., 2004a), which contained salt and fat ingredients. Shirsat et al. (2004a) conducted a study to determine the EC of meat emulsions containing different levels of salt and fat content. Table 4.5 represents part of their experimental data on the EC of some selected meat batter. Their results indicated that presence of salt or other electrolytic ingredients were essential for Ohmic heating, and higher electrical conductivity and Ohmic heating rates were associated with the high level of salt content. In addition, higher levels of added fat in the model batters had a reducing effect on the conductivity.

TABLE 4.3
Values of EC (S/m) for Meat Products at Different Temperatures

Product		Temperature (°C)							Reference
		25	40	60	80	100	120	140	
Chicken	Breast	0.665	0.873	1.142	1.386	1.678	1.948	2.212	Sarang et al. (2008)
	Tender	0.549	0.766	0.979	1.207	1.436	1.696	1.960	
	Thigh	0.348	0.472	0.607	0.772	0.962	1.137	1.322	
	Drumstick	0.444	0.598	0.763	0.974	1.182	1.399	1.601	
	Separable fat	0.035	0.057	0.090	0.128	0.158	0.184		
	Unknown	0.655	0.881	1.159	1.421	1.702	2.002	2.318	
Pork	Top loin	0.56	0.735	0.930	1.092	1.305	1.546	1.751	Tulsiyan et al. (2008)
	Shoulder	0.532	0.696	0.886	1.085	1.316	1.544	1.717	
	Tenderloin	0.584	0.750	0.957	1.155	1.407	1.695	1.961	
Beef	Bottom round	0.489	0.669	0.826	1.037	1.242	1.443	1.608	Sarang et al. (2008)
	Chuck shoulder	0.487	0.626	0.801	1.019	1.253	1.481	1.665	
	Flank loin	0.371	0.502	0.710	0.960	1.240	1.464	1.696	
	Top round	0.491	0.645	0.841	1.071	1.346	1.551	1.721	

TABLE 4.4
Published Values of EC (S/m) for Various Meat Products at 25°C

Food Material	EC	Reference
Chicken	0.08	Mitchell and de Alwis (1989)
	0.37	Palaniappan and Sastry (1991a)
	0.655	Tulsiyan et al. (2008)
Breast	0.665	Sarang et al. (2008)
Tender	0.549	Sarang et al. (2008)
Thigh	0.348	Sarang et al. (2008)
Drumstick	0.444	Sarang et al. (2008)
Pork	0.087	Halden et al. (1990)
Top loin	0.560	Sarang et al. (2008)
Shoulder	0.532	Sarang et al. (2008)
Tenderloin	0.584	Sarang et al. (2008)
Pork cuts (entire)		
Leg lean	0.76	McKenna et al. (2006)
Shoulder lean	0.64	McKenna et al. (2006)
Belly lean	0.68	McKenna et al. (2006)
Back fat	0.04	McKenna et al. (2006)
Belly fa	0.09	McKenna et al. (2006)
Pork cuts (minced)		
Leg lean	0.86	McKenna et al. (2006)
Shoulder lean	0.82	McKenna et al. (2006)
Belly lean	0.86	McKenna et al. (2006)
Back fat	0.01	McKenna et al. (2006)
Belly fat	0.05	McKenna et al. (2006)
Beef	0.44	Palaniappan and Sastry (1991b)
	0.42	Kim et al. (1996)
Bottom round	0.489	Sarang et al. (2008)
Chuck shoulder	0.487	Sarang et al. (2008)
Flank loin	0.371	Sarang et al. (2008)
Top round	0.491	Sarang et al. (2008)
Surimi		
1% salt	1.5	Yongsawatdigul et al. (1995)
2% salt	2.5	Yongsawatdigul et al. (1995)
3% salt	3.5	Yongsawatdigul et al. (1995)
4% salt	5.0	Yongsawatdigul et al. (1995)
Canned Pet food	0.097	Mitchell and de Alwis (1989)

Note: Values of McKenna et al. (2006) were measured at 20°C.

Higher moisture content in the food systems consistently showed higher electrical conductivity during Ohmic heating. An increase in electrical conductivity with moisture content in various proteins was also observed in other studies (Pethig, 1979; Yongsawatdigul et al., 1995). They reported that when more water molecules were available, ionic mobility possibly increased. Ionic conduction effects increase by being associated with salts in a hydrated sample. Therefore, higher hydrated proteins could allow protons and other ionic constituents to migrate around the surface of the proteins (Pethig, 1979).

Processing food containing solid particles including meat chops deals with the presence of different minerals, moisture, fat, and protein content which are the basic component of food materials as well as other value-added ingredients. Electrical conductivity as the key parameter in the Ohmic

TABLE 4.5
Electrical Conductivity of Meat Emulsion with Different Formulation

Formulation	Meat Emulsion Composition				Added Salt (%)	Conductivity (S/m)
	Lean (g)	Fat (g)	Water (g)	Salt (g)		
1	50	25	25	0	0	0.37
2	50	25	25	2.0	1.69	1.27
3	50	25	25	3.0	2.91	1.50
4	50	25	25	4.0	3.86	1.80
5	50	0	25	2.0	2.60	1.80

Source: Data from Shirsat, N. et al. 2004a. *Journal of Muscle Foods* 15:121–137.

Note: Conductivities taken at 50 Hz, 4 V cm⁻¹ and 15°C.

process would be affected by various percentages of any of these components in the food system. Further investigations are needed to have a good knowledge and estimate of the EC of the meat formulation undergoing Ohmic heating process.

4.4 ELECTRICAL CONDUCTIVITY DATA FOR FRUITS AND VEGETABLES

There are many different commodities defined as fruit or vegetables that could be served fresh or processed either as a single item or along with other materials. Variation among the agricultural products is relatively large compared to nonbiological materials due to the presence of the different varieties of fruits and vegetables as a result of plant breeding or geographical location of the production. The physical properties of biological materials, including EC, vary considerably among the varieties of the same commodity. Most of these products usually have to be blanched, soaked, peeled, and then cut into smaller pieces for processing applications. Any pretreatment such as soaking in a salt solution for instant, or other parameters such as shape, size, method of cutting (axial or radial direction), chemical composition, presence of minerals, level of moisture content, freshness, and peeling can significantly affect the EC of the chopped fruit and vegetable products being prepared for the Ohmic heating process. (repeated in the next section). Although many studies have been carried out to evaluate the EC of agricultural and horticultural products in the last two decades (Mitchell and de Alwis, 1989; Halden et al., 1990; Palaniappan and Sastry, 1991a; Kim et al., 1996; Legrand et al., 2007; Tulsiyan et al., 2008; Sarang et al., 2008) there is concern over the large number of items and variations among the commodities; not enough data exists in the literature. Available data on the EC at room temperature of some fruits, such as apples and pears, and vegetables such as potatoes, carrots, peas, and beans are tabulated in Table 4.6.

Electrical conductivities of three vegetables (potato, carrot, and yam) were determined experimentally through a study conducted by Palaniappan and Sastry (1991a), using a constant voltage power supply in a static Ohmic heating device. They also examined the effect of salt solutions on the electrical conductivity of the vegetable samples; their results showed that immersing them in salt solutions increased the conductivities of the vegetable samples. However, when the samples were soaked in water the conductivity was reduced, which can be caused by leaching of electrolytes.

Kim et al. (1996) carried out a pilot plant study of a continuous Ohmic heating process of particulate foodstuffs including potatoes, carrots, peas, and beef (EC ranging from 0.037 to 0.42s/m) using a starchy solution as the carrier fluid with a presence of 0.2–2% salt concentration (EC ranging from 0.3 to 4.3s/m). While most of the important issues involving a true continuous process such as residence time distribution, lethality and microbiological validation of low conductive biological products were investigated. They concluded that due to possible nonuniform conductivity

TABLE 4.6
Published Electrical Conductivities (S/m) of Various
Vegetable Foods at Room Temperature

Food Material	EC (S/m)	Authors
Potato raw	0.038	Mitchell and de Alwis (1989)
	0.040	Halden et al. (1990)
	0.320	Palaniappan and Sastry (1991a)
	0.037	Kim et al. (1996)
0.2% NaCl	0.370	Palaniappan and Sastry (1991a)
0.4% NaCl	0.360	Palaniappan and Sastry (1991a)
0.8% NaCl	0.430	Palaniappan and Sastry (1991a)
Carrot raw	0.130	Palaniappan and Sastry (1991a)
	0.041	Kim et al. (1996)
across axis	0.025	Mitchell and de Alwis (1989)
//to axis	0.042	Mitchell and de Alwis (1989)
0.2% NaCl	0.290	Palaniappan and Sastry (1991a)
0.4% NaCl	0.310	Palaniappan and Sastry (1991a)
0.8% NaCl	0.250	Palaniappan and Sastry (1991a)
Onion	0.022	Mitchell and de Alwis (1989)
Mushrooms	0.022	Mitchell and de Alwis (1989)
Cucumber	0.027	Mitchell and de Alwis (1989)
Turnip	0.026	Mitchell and de Alwis (1989)
Parsnip	0.025	Mitchell and de Alwis (1989)
Brussels sprouts	0.009	Mitchell and de Alwis (1989)
Tomato	0.045	Mitchell and de Alwis (1989)
Leeks		
across axis	0.007	Mitchell and de Alwis (1989)
//to axis	0.032	Mitchell and de Alwis (1989)
Celeriac	0.026	Mitchell and de Alwis (1989)
Celery	0.251	Tulsiyan et al. (2008)
Courgettes		
Skin on	0.017	Mitchell and de Alwis (1989)
Skinless	0.032	Mitchell and de Alwis (1989)
Pepper	0.048	Mitchell and de Alwis (1989)
Pear	0.041	Mitchell and de Alwis (1989)
	0.84	Sarang et al. (2008)
Apple	0.023	Mitchell and de Alwis (1989)
Golden apple	0.067	Sarang et al. (2008)
Red apple	0.075	Sarang et al. (2008)
Pineapple	0.037	Sarang et al. (2008)
Peach	0.17	Sarang et al. (2008)
Strawberry	0.186	Sarang et al. (2008)
Bean sprout	0.200	Tulsiyan et al. (2008)
Pea	0.17	Kim et al. (1996)
Blanched red bean	0.22	Legrand et al. (2007)

of the particulates there is a need for further investigation of particulate conductivities in order to ensure faster heating of particulates than of fluids.

Castro et al. (2004) determined the EC of different strawberry products such as pulp, filling, and topping subjected to different field strength and multiple thermal treatments. They presented results of their study graphically showing values of EC ranging from 0.01 to 0.5s/m depending on the

TABLE 4.7**Values of EC (Sm^{-1}) for Variety of Fruit Samples at Different Temperatures**

Product	Temperature ($^{\circ}\text{C}$)							Reference
	25	40	60	80	100	120	140	
Apple, golden	0.067	0.144	0.251	0.352	0.425	0.504	0.571	Sarang et al. (2008)
Apple, red	0.075	0.138	0.239	0.339	0.419	0.499	0.577	
Peach	0.170	0.307	0.541	0.738	0.941	1.123	1.299	
Pear	0.084	0.173	0.313	0.439	0.541	0.607	0.642	
Pineapple	0.037	0.141	0.245	0.348	0.432	0.506	0.575	
Strawberry	0.186	0.335	0.592	0.801	0.982	1.143	1.276	Tulsiyan et al. (2008)
Bean sprout	0.200	0.284	0.408	0.541	0.661	0.783	0.911	
Celery	0.251	0.497	1.001	1.639	2.125	2.462	2.712	
Mushroom	0.286	0.371	0.493	0.631	0.787	0.985	1.194	
Water chestnut	0.109	0.253	0.656	1.124	1.546	1.896	2.201	
Chow-mein sauce	2.230	2.934	3.941	4.896	5.793	6.603	7.350	
Soy sauce	8.912	10.746	14.199	17.678	21.310	24.128	26.314	

Source: Data from Sarang, S., Sastry, S.K., and Knipe, L. 2008. *Journal of Food Engineering* 87:351–356; Tulsiyan, P., Sarang, S., and Sastry, S.K. 2008. *International Journal of Food Properties* 11: 233–241.

product and experimental condition. The graph showed that EC increased with temperature for all the products and conditions tested following linear relations. It was also reported that EC depended on the strawberry-based product, and indicated that an increase of EC with field strength variation (0.3–0.8 V/m) was obvious for two strawberry pulps and strawberry filling, but not for strawberry topping or strawberry-apple sauce.

Recently, Sarang et al. (2008) and Tulsiyan et al. (2008) reported more data for six different fresh fruits (red apple, golden apple, peach, pear, pineapple, and strawberry) through the sterilization temperatures ranging from 25°C up to elevated process temperature as of 140°C, which is summarized and presented in Table 4.7. In all the cases, conductivities increased linearly with increasing temperature. They reported that, in general, fruits were less conductive than meat samples in their experiments and within fruits, peach, and strawberry were more conductive than apples, pear, and pineapple.

4.5 ELECTRICAL CONDUCTIVITY AS A DEPENDENT VARIABLE

Thermo-physical properties of biological materials such as thermal conductivity and thermal diffusivity are known as temperature-dependent parameters. Among the properties, electrical conductivity is not exceptional and it is recognized as a material characteristic, which is also strongly dependent on temperature. Many researchers have reported that EC generally increases with the increase in temperature (Palaniappan and Sastry, 1991a, b; Fryer et al., 1993; Reznik, 1996; Ruhlman et al., 2001; Zareifard et al., 2003; Castro et al., 2003, 2004; Tulsiyan et al., 2008; Darvishi et al., 2011). To design a safe and optimized Ohmic heating process for food materials, it is important to know the more accurate values of EC since it is a key parameter of the products undergoing process. It is essential to have a good knowledge of EC as a function of temperature ranging from room temperature to 80°C or 100°C. Sometimes values of EC are needed for a wider range from freezing point to 140°C depending on the purpose of the process: thawing, pasteurization, or commercial sterilization. Values of EC increase linearly with temperature up to 100°C; at higher temperatures it may be doubled or tripled than the given values at room temperature. However, under pressure when temperature exceeds 100°C, EC values may even increase exponentially. Therefore, attempts have been always made to evaluate and report the EC values of different agricultural, horticultural, and meat products not only at room temperature but also at more elevated temperatures. For example,

Ruhlman et al. (2001) reported EC values for liquid foods; and Sarang et al. (2008) and Tulsiiyan et al. (2008) reported values of EC for some meat products at given temperatures ranging from 20°C to 140°C, as already shown in Tables 4.2 and 4.3. Empirical regression equations have been also developed for different products that are valid for the given range of reported temperature. These mathematical equations are presented in the modeling chapter (Chapter 6).

Temperature is not the only parameter that has been considered important in the EC measurement of biological products. Other processing parameters such as pressure, applied voltage, wave forms, and frequency; or product parameters such as solid content, size, and shape of the solid particles are also among many factors that were taken into account for the evaluation of the EC of food materials. Some researchers have reported values of EC considering the above-mentioned factors for the given conditions as studied which will be discussed in the following sections. Again, as mentioned, considering the relationship between electrical conductivity and temperature, simple or multiple regression models have been developed for the prediction of EC, which will be presented in the modeling chapter.

4.6 ELECTRICAL CONDUCTIVITY: CONSIDERING FREQUENCY AND SOLID CONTENT

Measuring the EC of biological materials depends on many factors that could be divided into two categories: system and product parameters. In spite of temperature and voltage gradients that were discussed in the previous sections, there are other parameters related to the power supply systems such as frequency and wave forms that could be taken into account for the measurement of the EC of the materials undergoing Ohmic heating process. Other factors related to the product could be named as size, shape, solid concentration, and orientation of the solid particle in the electrical field, which also affect the overall resistance of the food matrices. In general, the EC of materials can be affected by any other parameters, like processing under pressure, that potentially could change the heating rate of the products being processed under Ohmic heating condition. Therefore, from the late 1980s food-processing investigators started exploring the relationships between the EC of foodstuffs and most of these factors.

Stirling (1987) brought up the idea of Ohmic heating as a new method for food processing as a rapid and fast method of heating. However, by applying Ohmic heating approach for several foodstuffs, based on the evaluated values of EC at room temperature, he classified food materials in three main categories as rapid heating (0.7–3.0 S/m), very rapid heating (0.05–0.52 S/m) and unsuitable biological materials (<0.03 S/m) for Ohmic heating due to very low conductivity. Table 4.8 presents some of the initially published values of the EC of a variety of foods at room temperature as grouped in the above-mentioned categories.

Lima et al. (1999) conducted experiments to investigate the electrical conductivity of turnip samples at four levels of low frequencies (4, 10, 25, 60 Hz) with three different waveforms (sine, saw-tooth, and square). Values of 0.033–0.474 S/m were reported as the EC of turnip at 30°C processed differently, while these values changed to 0.853–1.82 S/m at 95°C. These results indicated that for the sine and saw-tooth shaped waveforms, the EC measured at 4 Hz were significantly different than those at 10, 25, and 60 Hz. For the square wave case, the EC measured at the 4 Hz was higher than the other frequencies. Results of this study are summarized in Table 4.9. Chaiwanichsiri et al. (2001) also reported that the frequency had no remarkable effect on the EC of potato starch suspension (50 g/kg).

4.7 ELECTRICAL CONDUCTIVITY UNDER PRESSURE

Bauer and Knorr (2004) investigated the EC of wheat and tapioca starch suspensions (5% w/w) as affected by the degree of gelatinization after pressure treatment up to 530 MPa at a constant temperature (29°C) and different holding times up to 240 min. They found that by increasing pressure at a constant treatment time, the degree of gelatinization increased, resulting in a gelatinization curve similar to that of the conventional thermal gelatinization. A pressure increase also caused an

TABLE 4.8
Electrical Conductivity of Various Commodities at Different Heating Rates

Product Type	Heating Rate (°C/s)	ECy (S/m) at 25°C
Pickles and chutneys	Rapid heating possible	2.0–3.0
Savoury sauces	1–5°C/s	1.6–1.8
Various soups		1.4–1.8
Minced beef, lamb		0.8–1.2
Pet foods		0.7–1.2
Full-cream milk	Very rapid heating	0.52
Dairy desserts (vanilla/custard)	7–50°C/s	0.50–0.38
Beaten egg		0.4
Vegetable pieces		0.1–0.06
Fruit pieces		0.15–0.05
Margarine	Unsuitable products and conductivity	0.027
Sugar syrup	too low	0.001

Source: Adapted from Stirling, R. 1987. *Power Engineering Journal* 6:365–371.

increase in the EC of tested materials probably due to the release of ions during pressurizing. Values of 65–80 and 75–90 $\mu\text{S}/\text{cm}$ were reported for wheat and tapioca starch suspensions after pressurized treatment for the purpose of gelatinization.

Most researchers have evaluated the EC of food commodities at atmospheric pressure or slightly higher due to the build-up pressure during Ohmic heating inside the Ohmic cell. However, considering the application of hurdle technology in food processing areas such as the combination of Ohmic

TABLE 4.9
Mean Values of EC in S/m for Turnip Samples at Selected Temperatures for Different Wave Forms and Frequencies

Wave Form	Frequency (Hz)	Temperature (°C)			
		30	50	75	95
Sine	4	0.433	0.794	1.31	1.7
	10	0.107	0.406	0.778	0.961
	25	0.059	0.404	0.956	1.22
	60	0.033	0.318	0.758	0.967
Sawtooth	4	0.474	1.04	1.540	1.82
	10	0.165	0.457	0.780	0.965
	25	0.087	0.408	0.811	0.983
	60	0.039	0.418	0.794	0.962
Square	4	0.048	0.233	0.554	0.769
	10	0.042	0.167	0.432	0.646
	25	0.038	0.257	0.583	0.789
	60	0.042	0.217	0.603	0.853

Source: Data from Lima, M., Heskitt, B.F., and Sastry, S.K. 1999. *Journal of Food Process Engineering* 22:41–54.

TABLE 4.10
Values of EC for 0.01 m NaCl Solution at Different Pressures and Temperatures

Pressure (MPa)	Temperature (°C)	Electrical Conductivity (S/m)	Reference
100	25	0.131	Quist and Marshall (1968)
		0.130	Min et al. (2007)
200	25	0.132	Quist and Marshall (1968)
		0.140	Min et al. (2007)
300	25	0.134	Quist and Marshall (1968)
		0.130	Min et al. (2007)
400	25	0.130	Quist and Marshall (1968)
		0.130	Min et al. (2007)
	61	0.219	Xu et al. (1997)
		0.220	Min et al. (2007)
600	54	0.220	Xu et al. (1997)
		0.220	Min et al. (2007)
800	51	0.206	Xu et al. (1997)
		0.210	Min et al. (2007)

heating with other techniques such as ultra high pressure (UHP), values of EC under a pressurized system are also required. So far, only few researchers (Quist and Marshall, 1968; Xu et al., 1997; Min et al., 2007) have measured the EC of food materials using UHP and very limited data are available.

Quist and Marshall (1968) are probably the first who measured the EC of salt solution using UHP ranging from 100 to 400 MPa. Thereafter, Xu et al. (1997) measured the EC of 0.01 m NaCl solution at 0.4–5.0 GPa and the temperature range was 25–500°C. Their results indicated that the EC of the NaCl solution had little change with increasing pressure below 1.5 GPa, but rapidly changed with increasing pressure above 1.5 GPa. Reported values of EC for 0.01 m NaCl salt solution estimated under UHP conditions ranging 100–800 MPa by different researchers were compared in Table 4.10.

Min et al. (2007) measured the EC of 0.01 and 0.1 m NaCl and KCl solutions, apple juice, orange juice, and tomato juice, at pressures up to 800 MPa. The electrical conductivity of NaCl and KCl solutions were measured at 25°C and 50°C, whereas the EC of juices were measured only at 25°C. Their results indicated a significant effect of pressure on EC of salt solution and juices. Values of 0.25–0.30, 0.4–0.45, and 0.6–0.65 S/m were reported for apple, orange, and tomato juices, respectively, at pressure ranges of 0.1–800 MPa and 25°C. For all salt solutions and juices, EC increased with the increase in pressure up to a certain point (peaking between 200 and 500 MPa) and decreased thereafter.

4.8 CLOSING REMARKS

More data have been published on the electrical conductivities of liquid foods than for solid foods. Indeed, due to the complexity of food systems, only a few studies focus on evaluating the electrical conductivities of real food formulations such as those containing various ingredients; for example, meat formulations, or those containing both liquids and solids, for example soups. In reporting electrical conductivity data for a given commodity, variations can be expected due to: the nature of biological materials, different measurement approaches employed, and the use of different measuring devices. Earlier studies on conductivity were mostly performed at room temperature, whereas this property is highly temperature dependent. As such, caution must be taken while applying the existing values of electrical conductivities for a safe Ohmic heating process design. More recently, studies have provided empirical equations for the prediction of electrical conductivity of food materials as a function of influencing parameters including temperature, which will be presented in the following chapter.

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5 Factors Influencing Electrical Conductivity

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5.1 INTRODUCTION

The importance of electrical conductivity (EC) as a key parameter in the Ohmic heating process of food material was discussed in Chapter 3, methods of measurements were also explained and available data on the EC of different foods including liquids and solids were classified and presented for variety of fruits, vegetables, and meat commodities in Chapter 4. There are several parameters that can affect and change the values of EC for a given commodities, these parameters will be highlighted in this chapter. EC is a material property that has to be identified like other thermo-physical properties of materials such as thermal conductivity, thermal diffusivity, and heat capacity. These properties are not fixed values, and could be varied under different conditions especially for biological materials including foodstuffs. Therefore, attempts have been made to develop multiregression and empirical models to predict the EC of a given material as a function of most significant influencing factors. The existing models for numbers of food material will be discussed and presented in the following chapter.

The resistance of the material to the passage of current indicates the amount of generated heat in the system undergoing the Ohmic heating process (Skudder and Biss, 1987; Sastry and Li, 1996; Icier and Ilicali, 2004). This resistance or level of conductivity depends on so many factors that can be mainly categorized as product and system parameters. EC of materials being processed under Ohmic heating conditions were consider as the most important influencing parameter on process temperature and target lethality values as indicated by many researchers (de Alwis et al., 1989; Palaniappan and Sastry, 1991; de Alwis and Fryer, 1992; Tulsian et al., 2008, Chen et al., 2010).

Some of the product parameters can be named as temperature, ionic strength, free water (Lima and Sastry, 1999), material shape, size, and orientation (Sastry, 1992; Sastry and Palaniappan, 1992a) as well as the ingredient, and the ratio of solid to liquid in complex food matrices (Palaniappan and Sastry, 1991b, Marcotte et al., 1998; Castro et al., 2004; Zareifard et al., 2003; Keshavarz, 2011) or solid content in liquid foods such as juices and dairy products (Moura et al., 1999; Icier and Ilicali, 2004, 2005a; Kong et al., 2008; Sun et al., 2008). De Alwis and Fryer (1990), Sastry and Palaniappan (1992a), and Zareifard et al. (2003) reported that the particle size, concentration, and orientation have a significant effect on the heating rate and the overall conductivities of the foodstuffs containing solids. Furthermore, they found that food systems with lower EC had a longer heating time to achieve the target temperature; it showed that the EC decreased as particle size and concentration increased, while it increased linearly with temperature.

In the case of liquid foods, sometimes food industries use EC evaluation as a quality index. For example, in dairy industries, it is one of the testing methods in order to determine food qualities such as soluble salts (Crow, 1994), protein content in whey powder (Zhuang et al., 1997), and casein content during renneting (Dejmek, 1989). In some cases of veterinary practice it can be used as a diagnostic of intramammary infection (Woolford et al., 1998). Also in food processing companies, EC measurement has been used as a quality-control indicator during CIP procedure.

Therdthai and Zhou (2001) briefly reviewed some specific points concerning the influencing factors on the EC of liquid food such as milk. In liquids, EC is considered as a property involving the movement of anions to anode and cations to cathode, and the electron transportation to complete the current path (Loveland, 1986). Factors influencing the movement of ions include concentration, electric potential, temperature, and mechanical stirring (Crow, 1994). Chemical structure of a material also affects its EC. For instant, protein contains positive influence on EC (St-Gelais et al., 1995) whereas fat and lactose cannot conduct current. It has been reported that the EC of milk decreases as the concentration of fat and lactose increase (Prentice, 1962), while it always increases with temperature.

In addition to the above-mentioned factors concerning the material or product specifications, liquid or solid, there are other parameters related to the Ohmic heating system that can directly or indirectly affect the EC of the materials. These parameters include power supply specifications such as voltage gradient and frequency, electrodes design, cell size in static Ohmic unit or fluid flow characteristics in continuous tube-flow conditions (Halden et al., 1990; Palaniappan and Sastry, 1991a; Yongsawatdigul et al., 1995; Park et al., 1995; Wu et al., 1998; Lima and Sastry, 1999; Icier and Ilicali, 2004, 2005a,b; Pongviratchai and Park, 2007). It is well known that the EC of biological materials is a strong function of temperature and, therefore, attempts have been made to evaluate the EC of variety of food commodities at different temperatures and to develop empirical and regression equations to model EC as a function of temperature.

Each of the above-mentioned parameters can affect the EC. But this property could be more sensitive to some than the others. In a recent study, Chen et al. (2010) analyzed the process sensitivity of continuous Ohmic heating process for soup products containing liquid and large particulates by use of a validated computer modeling package to determine the critical control factors. Based on the this study, it can be concluded that for the Ohmic heating process used for producing fluid-particle foods, EC of both carrier fluid and particles are the most sensitive variables to the process temperature and target lethality values.

5.2 PRODUCT PARAMETERS

5.2.1 SIZE AND SHAPE

The Ohmic heating rate can vary considerably with particle size, and shape even for isotropic foods and with small changes in conductivity (de Alwis and Fryer, 1988; de Alwis et al., 1989). The effects

of shape on the heating rate are complex, but can be predicted using a suitable computer program as studied by de Alwis and Fryer (1990).

Solids content, in particular, is known to have a significant influence on the electrical properties of the slurry and may have a decisive effect on the performance of the heat-treatment process (Sastry, 1992; Zhang and Fryer, 1993; Sastry and Li, 1996; Sastry and Salengke, 1998). Likewise, for a given solids content, it is expected that solid particles' size and shape will induce significant changes in the EC of the mixture. Concerning Ohmic heating of solid food materials, the size and shape of the food samples are among the influencing parameters that can have an effect on the EC of the system. However, very limited studies had paid attention to this issue. For tomato and orange juices, Sastry and Palaniappan (1991) reported that reduction of the particle size of the juice's solid contents increased the effective EC of the juices. Using a mixture of carrot particles dispersed in starch solution, Zareifard et al. (2003) studied the effect of particle size ranging from very fine particle size as in puree, up to 6 and 13 mm cubic carrot particles. They found that the EC of the food system decreased as the particle size increased in a carrot–starch mixture. However, the effect of particle size was more enhanced at higher temperatures. Castro et al. (2004) examined the effect of particle size on the EC of strawberry products containing different solid content. The effect of particle size had been reported to be significant. For the equal solids content, they found that EC could be decreased up to 30% with increasing particle sizes. They presumed that by increasing the particle size, resistance of ionic movement could be increased, which results in reduction of the EC.

Though little information is available concerning the effect of shape on the EC for nonfood material such as rock and soil granular media or composite materials (Friedman et al., 2002, 2003, Wen-Zhong et al., 2006), no one has reported the effect of shape on the EC of the individual solid food particles or a mixture of solids dispersed in a liquid food media.

5.2.2 TEXTURE

Agricultural products including fruits and vegetables, as well as meat and dairy products usually experience aging through storage periods from the time of harvesting or slaughtering until the processing time. The storage time and conditions vary from hours to days and even months in some cases, while temperature and other parameters such as moisture and light may also change. Therefore, aging affects the appearance, chemical composition, and eventually the texture of the biological materials. Consequently, thermo-physical properties of these materials will be affected.

Halden et al. (1990) reported that the EC of food commodities was affected by starch gelatinization, fat liquefying, and cell structure changes of the food material. They used an aubergine (eggplant) slice in Ohmic heating and observed that a very marked change in the heating rate between 80°C and 95°C. They also observed that the structure breaks down almost completely, and large holes were formed which probably provided alternative path for the current. Similar, but less dramatic, physical changes were noted when Ohmically cooking strawberries. A considerable increase in the conductivity was noted at about 65°C, a change that was accompanied by a marked softening of the fruit, presumably due to a breakdown of the cell walls. The increase in the conductivity of strawberries results from breakdown of pectic substances and a resulting increase in ionic mobility.

Solid food like plant tissue is composed of individual cell units and surrounded by their cell membrane and cell wall. The major component of the cell membrane is phospholipid and can be assumed to behave electrically as a condenser (Sensoy and Sastry, 2004). The overall impedance of the food commodities is a function of their composition elements and their freshness. Therefore, it is likely that the Ohmic heating behavior may be affected as the impedance of the tissue changes.

In vascular plants, vascular bundles typically run along the stem of the plant. Considering the fact, that the constructive cells in stem tissues are usually irregular in shape and structure, hence, they might show different electrical behavior when a stem piece is placed in different directions. In this regards, Wang et al. (2001) studied the electrical conductance of bamboo, sugarcane, lettuce, and mustard, which are known as kinds of vascular plants. Sarang et al. (2008) reported that the EC

of strawberry and peach were higher than EC of apple, pineapple, and pear tissue. They concluded that this may be due to the softer tissues of strawberry and peach in comparison to the harder tissues of apples, pineapple, and pear. They also mentioned that the presence of air in the apple tissues could lower its EC.

5.2.3 VISCOSITY

Viscosity being a temperature-dependent parameter is another critical parameter that could affect EC; however, available data on the effect of the viscosity on EC are very limited. Conducting an experiment on a series of solutions of different viscosities (at 20°C) with similar initial conductivities, Fryer et al. (1993) reported that the viscosity had little or no significant effect of the EC. However, Singh et al. (2008) found that the EC of the juices (apple, pineapple, orange, and tomato) strongly depended on the viscosity.

Fryer et al. (1992) indicated that when a wooden cylinder was heated in an electrically conductive fluid, the fluid's heating rate increased with fluid viscosity, and they attributed this phenomenon to lack of convection in a high viscosity fluid, yielding high temperatures in the regions of maximum current density. This phenomenon of "heating rates being increased by lack of convection" has interesting implications in Ohmic heating of food matrix with high solids concentration, where many zones of high current density may exist (Khalaf and Sastry, 1996). Therefore, Khalaf and Sastry (1996) showed their interest on studying the effects of fluid viscosity on the Ohmic heating rates of fluid-particle mixtures. They used fluids of identical electrical conductivities but different viscosity values containing the same amount of solid particles (of EC lower than the fluid) in a batch (static and vibrating), and continuous Ohmic heating systems. In the static Ohmic heated system the heating rate of the fluid and particles was found to be comparable for the different fluids. However, in the vibrating Ohmic heater the heating rate of fluid and particles was found to increase with increasing fluid viscosity. In the continuous flow Ohmic system, the mixture with the higher viscosity fluid heated faster than that with the lower viscosity fluid. They related this phenomena to the poor interphase convective heat transfer, that contributes to accelerated overall heating, since the more (electrically) conductive phase does not lose heat readily to the less (electrically) conductive phase, and consequently heats rapidly, thereby transferring heat to the other phase by larger temperature differences.

5.2.4 INGREDIENTS

The EC of foodstuffs is highly affected by food ingredients. Since dissolved solids change the overall electrical resistance of the food matrix, they affect the effective EC (de Alwis and Fryer, 1992). Dissolved ingredients such as salts and acids have an increasing effect on EC whereas fat has a decreasing effect. The effect of salt (or other electrolytes) on the conductivity of different food systems was investigated by several researchers. By soaking potato pieces in salt solutions at different concentrations, Palaniappan and Sastry (1991a) found that, as the concentration of salt absorption increased, the EC values also increased along with temperature rise and the resulting heating rates. The effect of salt diffusion into potato tissue was also investigated by Wang and Sastry (1993) as a pretreatment for Ohmic heating. They found that the EC had a direct relationship with the level of salt concentration. The relationship was stronger when the amount of salt exceeded 0.01 g/cm³ in the tissue. However, for a high concentration brine, the σ -T relationship was nonlinear and followed quadratic models. The effect of the salt content of fish product emulsions (e.g., surimi) on EC as influenced by composition and temperature was considered as an important parameter in the EC modeling by Yongsawatdigul et al. (1995). The level of NaCl was found to significantly affect EC values in frozen seafood during Ohmic thawing; the treatment was more efficient at higher salt concentrations (Luzuriaga and Balaban 1996). The increasing effect of salt on the EC of different hydrocolloids was reported by Marcotte et al. (2000). They found that for all hydrocolloid solutions the increasing effect

was more pronounced at high temperatures. They also examined the effect of added citric acid on electrical conductivities at normal and modified pH for different hydrocolloids. Their results revealed that there was little difference in the EC values for both the conditions. The reason for this might have come from the fact that being an organic acid, citric acid is not strongly dissociated. Despite the large pH differences provided, the differences in electrical conductivities profiles were not sufficient. Shirsat et al. (2004a) reported that the increase of salt content in meat batters had an increasing effect on its EC, while an increase in fat content had a reducing effect on the EC.

Palaniappan and Sastry (1991a) found that the EC of the vegetable tissues increased with infusion of salt solutions, however, the amount of increase depended on the salt concentration. The dependence of EC to salt concentration was less at low temperatures; however, the conductivity of samples showed an increasing trend with salt concentration for higher temperatures. The existence of concentration gradients within the samples at the time of testing was provided as the possible reason for this behavior. Similarly, Wu et al. (1998) reported that the salt content had affected the EC of surimi at the frequencies of 30 Hz to 1 MHz. Castro et al. (2004) found that the presence of sugar caused a decrease of up to 60% in the conductivity of strawberry pulp. This decrease can be related to the nonionic property of sugar that can cause a decrease in EC as stated by Sastry (1992). Sarang et al. (2008) have mentioned that one of the most important factors influencing the conductivity of fruit and vegetables is the total ionic content. The measurement of the total ionic content—sugars and salts—and comparison of the conductivity based on the ionic contents is a topic for future study.

Halden et al. (1990) showed that the EC of food materials can be affected by melting of fats, starch transition, and cell structural changes during Ohmic heating of pork, potato, and aubergine samples. These changes may be due to enhanced diffusion of cell fluids and electro-osmotic dehydration, as possible in the presence of an electric field. For potato samples, EC changed significantly at higher temperature where starch starts to gelatinize. They also reported that the increase in EC mainly occurred at temperature between 20°C and 40°C and above 60°C, where the main changes in the food structure take place. The effect of starch gelatinization on EC was also reported earlier by Stepanov et al. (1982).

The effect of native and pre-gelled potato starch at different concentrations on EC of surimi based product with different moisture contents was investigated by Pongviratchai and Park (2007) using a multi-frequency Ohmic heating unit operated with different frequencies ranging from 55 Hz to 20 kHz and a voltage gradient of 4.3 and 15.5 V/cm. Their results showed that the moisture content, applied frequency, and applied voltage had a direct effect on the EC of surimi products; however, starch concentration had a decreasing effect on EC. It was reported that the EC of surimi products containing potato starch decreased as starch concentration increased, while the EC had an increasing linear trend with temperature.

In meat samples, there is one possible problem in the Ohmic heating process; if pork meat and fat were Ohmically treated together, the two solid materials would heat at different rates (Halden et al., 1990). Therefore, during the time of processing, conduction effects may not give thermal equilibrium; so that process must be designed to sterilize the component that heats the slowest. In muscle cuts, fat distribution (called marbling) could possibly play an important role in the overall EC of samples. Sarang et al. (2008) found that the separable fat (in meat) has significantly decreased the conductivity compared to lean muscle cuts. McKenna et al. (2006) also reported that the conductivity of fat was considerably lower than lean meats.

5.2.5 ORIENTATION

It is reported that the particle orientation in an Ohmic heating system affects the EC of the solid particles located in the electrical field (de Alwis et al., 1989; de Alwis and Fryer, 1990; Sastry and Palaniappan, 1992; Zareifard et al., 2003). In a food system, a particle can rotate about in any direction; however, rotations about the direction of the electric field do not change the effective resistance. Rotation about any other direction produces different cross sections of the particle facing the

current (Sastry and Palaniappan, 1992), which could cause different resistance in particle. This in turn will affect the EC of the food particle and system. After conducting simulation processes with different scenarios on a potato particle (cubes of 0.01 m), Sastry and Palaniappan (1992a) reported that the orientation had little effect ($\leq 10\%$) on the resistance of the mixture.

Wang et al. (2001) found that the electric conductance was affected by the direction of the stem in vascular plants such as bamboo shoots and sugarcane. The electric conductance along the stem was higher than the electric conductance across the stem in bamboo shoots and sugarcane. However, lettuce and mustard stem have shown opposite reactions. This could be resulted from the natural structure of these plants. It is known that bamboo and sugarcane belong to monocotyledons, while lettuce and mustard belong to dicotyledons. These two types of plants have different stem infrastructure (Stern, 1994).

Evaluating the EC of a two-phase food systems containing carrot cubes immersed in a starch solution by Zareifard et al. (2003), showed that the heating behavior of the solid and the liquid phase could be reversed depending on whether the mass of particles were placed in parallel, in a series or in a well-mixed system. Although the heating behavior was different, very slight changes in values of the overall electrical conductivities of the two-phase food systems were reported.

5.2.6 MOISTURE CONTENT

It is reported that in liquids the electric current is carried by movement of ions (Shirsat et al., 2004b). Therefore, the EC of liquid depends on the amount of freely movable ions in the liquid. Increase in temperature can cause an increase in ionic movement due to conversion of some of water into vapor at approximately 50°C (Kong et al., 2008). The increasing effect of moisture content on EC of foodstuff was reported for the Ohmic heating system in literature. This was related to the possible increase in ionic mobility resulting from the availability of more water molecules. An increase in Pacific whiting surimi paste's EC was observed by Yongsawatdigul et al. (1995), which was related to the possible increase of ionic mobility. The increasing effect of moisture content on the EC of surimi–starch paste was also reported by Pongviratchai and Park (2007).

5.2.7 SOLID CONTENT

The effect of solid content concentration on the EC of a solution depends on the size of solid particles in the carrier fluid, and whether the solid is soluble or not. Insoluble solid particle's sizes may vary from very fine nanoparticles in a homogenized solution to medium size solid particles like pulp in juice to a very large size solids of about one inch cubes, as with meat or vegetable chops, in a real two-phase food matrix such as soup. The effect could be different and even opposite depending on the nature of food mixture. The solid content may be dissolved in the solution as in the case of salt, sugar, acid, and starch concentrations or just be dispersed and scattered in the liquid phase. The effect of solid content on the EC was investigated using different a food system. Palaniappan and Sastry (1991b) reported that the solids content has a decreasing effect on electrical conductivities of tomato and orange juices where the solid size was in range of a fraction of millimeter. Similarly, Castro et al. (2004) found that the solid content had an important decreasing effect on the EC of a strawberry product. However, the effect was more significant for the product case containing bigger particle sizes. They reported that with the increase of particle size, a decrease of up to 30% in EC was observed for the same solid contents.

The effect of solid concentration on the EC of tangerine, pineapple, and lemon juices was also investigated by Moura et al. (1999) at different temperatures ($20\text{--}80^{\circ}\text{C}$). They found that the concentration had a direct effect on the EC of the juices studied. EC increased with the increase of concentration up to a certain level (about 30°Brix) and thereafter it started to decrease. The decrease in EC can be related to the decrease in the mobility of the ions, which occurred with the increase in viscosity of the juices with concentration.

Using different types of hydrocolloids solutions (carrageenan, xanthan, pectin, gelatin, and starch with different concentration), Marcotte et al. (1998) found that the concentration had an increasing effect on the EC of the different hydrocolloid solutions containing a different percentage of salt concentrations.

Icier and Ilcali (2004) also reported that the concentration had a decreasing effect on the EC values of fruit juices (apple and sour cherry concentrates ranging from 20% to 60%) following a nonlinear relationship. The same trend was observed while the voltage gradient changed from 20 to 60 V/cm. This is in agreement with the decreasing effect of insoluble solid contents, reported by Palaniappan and Sastry (1991b), on the electrical conductivities of orange and tomato juices, but with a linear relation.

Not much has been published on the electrical conductivities of two-phase food systems containing large solid particles at various concentrations immersed in a liquid carrier. Zareifard et al. (2003) studied the effect of large size (6–13 mm) carrot cubes at different concentrations ranging from 0% to 60% dispersed in a 4% starch solution media. A longer heating time and lower values of EC were reported for food systems containing higher concentration of solid particles regardless of particle size.

5.3 SYSTEM PARAMETERS

5.3.1 TEMPERATURE

Temperatures could be considered as a system parameter, a target process temperature for instance or, it may also be considered as a product parameter, the initial or final temperature of liquid and solid materials undergoing a process, for example. No matter whether it is a product or system parameter, it is well understood that the EC of foodstuff as one of the thermo-physical material properties, is temperature-dependent, like thermal conductivity and diffusivity. The effect of temperature on the EC of different food materials have been investigated by many researchers (Halden et al., 1990; Fryer et al., 1993; Yongsawatdigul et al., 1995; Wang and Sastry, 1997; Roberts et al., 1998; Marcotte et al., 1998; Zareifard et al., 2003, and others), and it has always been reported that the EC increases with temperature. Generally speaking, the EC of biological materials increases linearly with temperature, unless in specific situations where phase transitions can occur for the components (e.g., starches gelation, fat melting) during heating (Shirsat et al., 2004b; Wang and Sastry, 1997b). For example, Karapantsios et al. (2000) found that during conventional heating of starch, the EC increased linearly with the increase in temperature until the gelatinization temperature, and thereafter had a decreasing trend.

Yongsawatdigul et al. (1995) reported that, an increase in temperature resulted in an increase on the EC of the Pacific white surimi during Ohmic heating. The effect of temperature depends greatly on the nature of the suspended solids. It is reported that with an increase in temperature, structural changes occur in the biological tissue, like cell wall protopectin breakdown, expulsion of nonconductive gas bubbles, softening, and lowering in aqueous phase viscosity. These structural changes will result in the increase of the ionic mobility, which in turn causes an increase in EC (Bean et al., 1960; Sasson and Monselise, 1977; Palaniappan and Sastry, 1991a; Sarang et al., 2008). The increase in the EC values with temperature has been related to reduce drag for the movement of ions.

Values of electrical conductivities for variety of foods were classified and presented in Chapter 4 at different temperatures. However, for a better process design (target lethality achievement) and modeling purpose (prediction of the coldest point temperature), regression models and empirical equations (EC as a function of temperature) are needed to apply more realistic values of EC at different temperatures during the process, which is from room temperature until desired processing temperature (pasteurization or sterilization). For example, Sastry and Palaniappan (1992a,b) and recently Salengke and Sastry (2007a,b) performed computational modeling and experimental investigations for the cases, where a less conductive particle is surrounded by a highly conductive

medium and heated Ohmically under a static condition where there is a need of empirical equations that can predict the values of EC at a given temperature for a better analysis. Therefore, mathematical models have been developed for different commodities as a function of temperature, which will be given in Chapter 6 for further application.

5.3.2 VOLTAGE GRADIENT AND WAVE FORM

Voltage gradient has been reported as another significant variable in Ohmic heating, which has increasing effect on EC (Halden et al., 1990; Palaniappan and Sastry, 1991a; Icier and Ilicali, 2004). This increase is mainly due to application of voltage, the so-called electro-osmotic effects, which cause fluid motion through the capillary porous membranes of the biological tissues (Halden et al., 1990; Palaniappan and Sastry, 1991). Icier and Ilicali (2004) reported that with the increase in voltage gradient the ampere passing through the system reached higher values especially at lower temperatures, which caused a violent evaporation of water in the samples. Therefore, the samples could not be heated to a higher temperature (up to 80°C). Similar effects of high-voltage gradient were reported by Lima and Sastry (1999). In the case of Pacific white surimi, Yongsawatdigul et al. (1995) reported that the voltage gradients had little effect on EC of surimi paste during Ohmic heating. The effect of the voltage gradient on EC of fresh strawberry and strawberry products was investigated by Castro et al. (2004). They found that the EC generally increased linearly with increasing field strength. The effect of field strength was less evident for strawberry pulp as compared to the fresh strawberries or strawberry jelly. This behavior was related to the occurrence of texturizing agents, which get activated with the rise of temperature and reduces the mobility of the fluid and of the ionic components present in the food material. However, they also reported some discrepancy in the results. These differences in the conductivity dependence on temperature were related to non-uniform tissues containing unripe segments (having higher cell wall resistance to destruction during heating) as highlighted by Sasson and Monselise (1977). An increase in the EC of surimi–potato starch with applied frequency and voltage was also reported by Pongviratchai and Park (2007).

As the voltage gradient decreases, the EC profile as a function of temperature becomes sigmoidal with a sharp transition around 60°C (Marcotte, 1999). Sigmoidal curves are also obtained during conventional heating conditions, which would represent a field gradient of about 0 V/cm. For a sufficient voltage gradient, the EC of solids varies linearly with temperature. Palaniappan and Sastry (1991a) reported that electrical conductivities of solid food pieces decreased with decreasing voltage gradient especially at 20°C. Values reported by Mitchell and de Alwis (1989) for solid food pieces appear to have been gathered at 20°C with a very low voltage gradient. Palaniappan and Sastry (1991a) tried to explain the reasons for the changing shape of the curve with increasing applied voltage. This phenomenon was attributed to electro-osmotic dehydration with a consequent tissue softening (Halden et al., 1990; Palaniappan and Sastry, 1991a) high-applied electric field enhanced cell fluids motion within plant cells and ruptured cell membranes.

Several authors (de Alwis et al., 1989; Palaniappan and Sastry, 1991b; Crow, 1994; Yongsawatdigul et al., 1995) have reported that there is no voltage gradient effect on electrical conductivities of liquids. According to Crow (1994), when applying only a few volts to electrolytic solutions, there is no measurable variation in EC with the voltage gradient, but at 100 kV/cm some differences may be observed. Palaniappan and Sastry (1991b) reported no effect of voltage gradient (30–60 V/cm) on the EC of orange juice, a low viscosity fluid. Yongsawatdigul et al. (1995) found that a high salt concentration (3–4%) in surimi must exist to observe an effect of voltage gradient on EC. They attributed this phenomenon to corrosion of the electrodes since it is unlikely that motion of cell fluids would be enhanced in homogeneous liquids.

It was shown that not only the voltage but also the wave form could have an effect on the EC of the food materials. The effect of a waveform on the EC of food stuff during Ohmic heating was studied by a few researchers (Kim and Pyun, 1995; Lima et al., 1999; Sensoy and Sastry, 2004). During the Ohmic heating process of soymilk extraction from soybeans, Kim and Pyun (1995)

found that the efficiency of the square wave was less than the sine wave. Moreover, they reported that when the pH of the extraction process was between 7 and 8 for the square wave, changes in the dissociation of chemical constituents occurred. The effect of the waveform (sine, square, and sawtooth) on EC of turnip samples was investigated by Lima et al. (1999). For all applied frequencies, their results indicated that the square waveform demonstrated lower EC values than the sine and sawtooth wave forms, especially at 4, 10, and 25 Hz. In another study conducted by Sensoy and Sastry (2004) the effect of waveform (sinusoidal, square, and triangular) on mushroom samples (cylinders) was investigated. Although there were some differences between EC values obtained from different waveforms (especially between triangular and other), they concluded that effect of waveform was not significant in their study.

5.3.3 FREQUENCY

Though many researchers (Falkenhagen, 1934; Mitchell and de Alwis, 1989; Park et al., 1995; Imai et al., 1995, 1996; Reznick, 1996; Wu et al., 1998; Lima et al., 1999; Angersbach et al., 1999; Chaiwanichsiri et al., 2001; Sensoy and Sastry, 2004; Singh et al., 2008) have evaluated the effect of frequency on the EC of the biological material, it is not yet clear how materials behave while frequencies vary from very low (1 Hz) to very high (30 MHz) and, therefore, some discrepancy and contradiction exists in the literature. The EC of fluids containing large amount of dissolved or entrapped ions, such as high moisture content materials, may be strongly influenced by frequency (Falkenhagen, 1934; Mitchell and de Alwis, 1989).

It is known that electrolysis effects exist for DC and also for AC currents at low-frequency (50–60 Hz) levels. Therefore, many systems have been developed using higher frequencies (100 Hz) to avoid this problem as well as to prevent the dissolution of metallic electrodes (Remik, 1988; Reznick, 1996). Evaluating the EC of the biological materials in an Ohmic heating system, while varying the frequency (reported up to 30 MHz), is important not only to realize different heating behavior of the materials, but also to control the extent of polarization during the measurement. This depends on several factors such as the nature of the electrode surface and the frequency of the alternating current. The restrictions arising from the electrode surface impose a choice on the material. Normally, treated or coated electrodes are used with the frequency found in the range of commercial instruments (50–1000 Hz). Increasing the frequency of the applied voltage can reduce polarization. The effect of frequency is particularly important for the range of measured electrical conductivities for foods (Cummings and Torrance, 1985).

The heating rate of food materials depends on the frequency of alternating current during Ohmic heating (Park et al., 1995; Imai et al., 1996; Wu et al., 1998), especially in solid food which is made up of individual cell units surrounded by their wall and cell membrane. It has been reported that if the food sample does not have a cellular structure, the heating rate can be increased by using high frequency, while foods with cellular structure, like vegetables, shows different results with changes in frequency (Sensoy and Sastry, 2004). Mitchell and de Alwis (1989) reported that a carrot sample had a conductance of 5×10^{-4} S and 1.1×10^{-2} S when measured at 50 Hz and 50 kHz. For fish protein gel (prepared from Alaskan pollack), Park et al. (1995) reported that the heating rate at 10 kHz is 7.5 times greater than that at 50 Hz. Also, Imai et al. (1996) found that heating rate of egg albumin solution slightly increased as frequency increased. The maximum heating rate was found at 10 kHz.

For foods with cellular structure, Imai et al. (1995) studied the effect of frequency on heat generation in a Japanese white radish using a variable frequency system in the range of 50 Hz to 10 kHz and a voltage gradient of 40 V/cm. However, their results indicated that the sharpest initial temperature rise was obtained with the lowest frequency (50 Hz), which is caused by the reduced impedance resulting from increased permeability and molecular movement. The main element of a cell membrane is a phospholipid that can be referred to, electrically, as a condenser. The impedance of the sample was remarkably reduced when heated to 60°C. They presumed that the cell structure, especially the membrane of the sample, is damaged above 50°C leading to a reduction in impedance.

This reduction of impedance probably results in the similar heating rates above 60°C regardless of the frequency used for Ohmic heating.

Lima et al. (1999) demonstrated that the EC of turnip tissue was higher at a lower frequency (at 4 Hz compared to 60 Hz) and the tissue heats faster at a lower frequency. Frequency dependency of the EC of plant tissue can be explained by electrical properties of a cell membrane, which can be represented as a resistor and capacitor (Angersbach et al., 1999). Increased permeability or mobility of molecules caused by the applied electric field increases the tissue's EC (Sensoy and Sastry, 2004).

It has been shown that for fluids with a high concentration of dissolved or entrapped ions, the EC is a strong function of the frequency (Falkenhagen, 1934). For commercial applications, the choice of frequency is usually a compromise between avoiding polarization problems without introducing capacitive errors into the measurements (Mitchell and de Alwis, 1989; Fryer et al., 1993; Kim et al., 1996a). Since the frequency effect is important with respect to EC values, it is necessary to measure electrical conductivities in the context of Ohmic heating at 60 Hz. There is little published information on the electrical properties of foods at low frequencies in the context of Ohmic heating (Mitchell and de Alwis, 1989).

Recently, Chaiwanichsiri et al. (2001) reported that the frequency (ranged between 200 kHz to 30 MHz) had no effect on the EC of potato–starch suspension (50 g kg⁻¹) measured at different temperatures (24°C, 60°C, and 82°C). While, more recently, Singh et al. (2008) studied the EC of juices (apple, pineapple, orange, and tomato) at two frequencies (1 and 10 kHz) and reported that the EC affected by the frequency, and all juices had higher conductivity at higher frequency.

5.4 CLOSING REMARKS

Knowledge of the parameters that influence EC measurement is important in its evaluation while performing experiments. Food materials undergo a temperature increase during the Ohmic heating process and, therefore, EC should be evaluated within the processing temperature range. For a safe industrial Ohmic heating process, a validation of the estimated EC of the products is recommended using the assigned processing system in the plant. Processors must be aware of any changes in food formulation undergoing the Ohmic heating process as varying the ingredients could significantly change the resistance of the food and, therefore, change the heat generation attributed to the current flow. A real food matrix is usually composed of solid particles and liquid. The components which receive the minimum heat are the critical ones to be considered for a safe process. In contrast to the traditional heating process where liquids heat up faster than solids, in Ohmic heating solid particles may heat up faster than liquids, as heating depends on the EC of each component. The eEC of solid foods can be modified and adjusted by soaking in salt solution if necessary.

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6 Modeling of Electrical Conductivity in the Context of Ohmic Heating

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6.1 INTRODUCTION

The importance of electrical conductivity methods of measurement and the influencing factors were already discussed in previous chapters, and the experimentally measured values of electrical conductivity (EC) for different commodities reported in the literature were presented in Chapter 4. It has been mentioned that in using the Ohmic heating process for foodstuffs, electrical conductivity, as a material property, plays an important role for the design and optimization of the processes. Therefore, knowledge of the electrical conductivity is essential for a safe process design. The worst-case scenario or the extreme condition (the cold spot in the food matrix being processed) should be taken into account while designing the process. For this purpose it is necessary to have a true understanding of the components' resistance that represents extreme conditions or slowest heating conditions. When heterogeneous foods (liquids with suspended solid particles) are processed by these methods, the liquid acts as an intermediate heat transfer medium, and thermal lags exist within particles. Modeling is a suitable method to provide useful information and examine different scenarios, as well as to predict the particle's temperature and monitor the coldest point during process. Particle temperatures were conservatively estimated by models (Sastry, 1986; Chandarana and Gavin, 1989; Lee and Singh, 1988, among others). The particle could be oriented in different directions, resulting in the problem becoming more difficult (Sastry and Palaaniappan, 1992b). There have been some works in computational modeling for the last two decades (de Alwis and Fryer, 1990; Sastry, 1992; Zhang and Fryer, 1993; Davies et al., 1999; Khalaf and Sastry, 1996; Ye et al., 2004; Salengke and Sastry, 2007; Shynkaryk and Sastry, 2012) concerning thermal behavior of food materials undergoing the Ohmic heating process, which is not the interest here. These models mainly simulate the temperature profiles of the liquid and solid components in the food system during Ohmic heating, which is necessary for the process design. However, one of the main inputs to these computational models is the EC of the materials.

Therefore, numerous mathematical and empirical models for the prediction of the electrical conductivity of food materials as a function of different influencing parameters were developed over years by many researchers (Palaniappan and Sastry, 1991a,b; Yongsawatdigul, 1995; Wang and Sastry, 1997; Wu et al., 1998; Moura et al., 1999; Marcotte et al., 2000; Castro et al., 2003; Ayadi et al., 2004; Icier and Ilicali, 2004, 2005a,b; Assiry et al., 2006; Pongviratchai and Park, 2007; Singh et al., 2008), and those models are of interest here. There are also some models in the literature that can be used to determine effective electrical conductivities of two-phase mixtures (Maxwell, 1881; Meredith and Tobias, 1960; Kopelman, 1966; Brailsford and Major, 1964; Assiry et al., 2006; Zhu et al., 2010); however, applications of these models are limited only to dilute spherical particle dispersions (Sastry and Palaaniappan, 1992a).

Dealing with solutions, the electrical conductivity can be considered as a measure of the flow electrons, where anions move to anode and cations move to cathode (Loveland, 1986; Therdthai and Zhou, 2001). Therefore, it is important that a proper, integrated modeling method, which can account for determination of limiting conductivities of ions and the ionic pattern dependence of conductivity at finite concentrations, be developed as stated by Anderko and Lencka (1997). The mobility of ions in the infinite-dilution can be characterized by the limiting ionic conductivities, which indeed can provide a starting pathway for determining the electrical conductivity and finite concentration.

Reported values for the EC of food materials are valid for the specified conditions (e.g., a given temperature, a known salt or solid content, a set voltage, and frequency) whereas this property is strongly dependent on several factors and that is why multi regression models are required for its prediction and application. Measuring the EC of biological materials depends on many parameters that can be divided mainly into two categories: system and product parameters. Concerning system parameters, in spite of temperature and voltage gradients, there are other parameters related to the power supply systems such as frequency and waveforms that could highly affect the EC of the materials, which undergo Ohmic heating processes. Other factors related to the product could be size, shape, percentage, and orientation of the solid content in the electrical field which basically affects the overall resistance of the system. Any other parameters, like under pressure, that can change the rate of heating during the Ohmic heating process directly affects the electrical conductivity of the materials as well. Food processing investigators have started exploring some of these influencing factors on the EC of foodstuffs for the last two decades. Simple linear or nonlinear and multiple regression models have been developed by a group of researchers and are available in literature. These models are classified based on the temperature, voltage, and solid content dependency and will be presented in the following sections.

6.2 ELECTRICAL CONDUCTIVITY: TEMPERATURE DEPENDENCY

For modeling purposes there is a need of empirical equations that can provide the values of EC over the range of the processing temperature. Therefore, many researchers investigated the electrical conductivity–temperature relation for different liquid and solid food materials. The electrical conductivity–temperature relationship was found to be linear for most of the foodstuffs. However, some researchers have developed nonlinear models to simulate EC as a function of temperature. In this section, is a collection of available models for different materials and classification of them on a commodity basis.

de Alwis and Fryer (1990) investigated the Ohmic heating behavior of lamb meat pieces ($20 \times 20 \times 15$ mm) and potato pieces ($40 \times 10 \times 20$ mm) in a saline solution. They constructed a cell to measure the EC of the solid and liquid at different temperatures. They found that for lower temperature ranges the meat and liquid heated similarly, but differently at higher temperature; however, for potato both the phases heated differently. Furthermore, they developed the following equations for EC as a function of temperature:

$$\sigma_{\text{lamb}} = 0.344 + 6.8 \times 10^{-3}(T - 273) \quad (6.1)$$

$$s_{Potato} = 0.074 - 2.5 \times 10^{-3}(T - 273) + 4.7 \times 10^{-5}(T - 273)^2 \quad (6.2)$$

Palaniappan and Sastry (1991a) proposed the following equation for three vegetables (potato, carrot, and yam) while processed as raw materials and also soaked in water and sodium chloride solutions as well as raw beef and chicken pieces to simulate electrical conductivity–temperature relationship:

$$s = s_o(1 + a(T - 25)) \quad (6.3)$$

where, σ is the EC at a given temperature and σ_o is the reference EC in S/m measured at 25°C, α is the temperature constant, and T is temperature (°C). The proposed model was then used by Marcotte et al. (1998) and Ayadi et al. (2004) to identify the model's parameters for other foodstuffs such as hydrocolloid and protein-based liquid solutions, and later followed by Sarang et al. (2008) for some fruits and meat products. Reference values of the EC and temperature constants as in Equation 6.3 reported by these researchers are gathered in Table 6.1 for a number of commodities.

Wang and Sastry (1997) conducted experiments to study changes in EC for potato, carrot, and yam samples using a cyclic Ohmic heating treatment and preheated by conventional heating prior to Ohmic heating. Their results indicated that the preheated vegetables had higher conductivities than fresh ones, and an increased tendency in EC by cycles was also reported. Furthermore, they simulated the conductivity–temperature relations as

$$\sigma = \sigma_{30} + \alpha T \quad (6.4)$$

where the referenced EC values (σ_{30}) and temperature constants (α) for the tested materials are presented in Table 6.2.

The electrical conductivity of stabilized mince fish (made from Pacific whiting fillets) was measured by Wu et al. (1998) using a multifrequency Ohmic heating system with 30 Hz to 1 MHz, which could deliver 250 W. As expected, the values of direct current (DC) electrical conductivity of stabilized mince fish increased with the increase in temperature. Using the experimental data of the DC electrical conductivity for stabilized mince fish, the following empirical model was developed to relate EC with temperature.

$$\sigma = 0.262 + 0.0193T \quad (6.5)$$

Four linear regression models were proposed by Davies et al. (1999) to estimate the EC in S/m as a function of temperature ranging from 20°C to 95°C for water, CMC solution, solidified agar gel, and egg albumen aqueous solutions in the following Equations 6.6 through 6.9, respectively:

$$\sigma = 0.0398T + 0.8382 \quad (6.6)$$

$$\sigma = 0.0405T + 0.8859 \quad (6.7)$$

$$\sigma = 0.0412T + 0.9479 \quad (6.8)$$

$$\sigma = 0.0952T + 2.1595 \quad (6.9)$$

In another study, Marcotte et al. (2000) investigated the heating behavior of four different hydrocolloid solutions with four levels of salt concentrations ranging from 0.25% to 1%, which could be used as a carrier fluid in the Ohmic heating process of particulate foods. They again applied the same model as Equation 6.3 to simulate the EC of the solutions as a function of temperature. Values

TABLE 6.1
Empirical Model's Parameters for the Prediction of EC of Different Commodities

Material	σ_{25} (s/m)	α (°C) ⁻¹	Reference
Potato			Palaniappan and Sastry (1991a)
Raw	0.320	0.035	
Water	0.250	0.030	
0.2% NaCl	0.370	0.028	
0.4% NaCl	0.360	0.033	
0.8% NaCl	0.430	0.027	
Carrot			Palaniappan and Sastry (1991a)
Raw	0.130	0.107	
Water	0.120	0.078	
0.2% NaCl	0.290	0.044	
0.4% NaCl	0.310	0.044	
0.8% NaCl	0.250	0.062	
Yam			Palaniappan and Sastry (1991a)
Raw	0.110	0.094	
Water	0.090	0.079	
0.2% NaCl	0.420	0.021	
0.4% NaCl	0.350	0.032	
0.8% NaCl	0.350	0.034	
Chicken (raw)	0.370	0.019	Palaniappan and Sastry (1991a)
Beef (raw)	0.440	0.016	
Fruits			Sarang et al. (2008)
Apple, golden	0.089	0.049	
Apple, red	0.079	0.057	
Peach	0.179	0.056	
Pear	0.124	0.041	
Pineapple	0.076	0.060	
Strawberry	0.234	0.041	
Chicken			Sarang et al. (2008)
Breast	0.663	0.020	
Tender	0.567	0.021	
Thigh	0.329	0.026	
Drumstick	0.428	0.024	
Separable fat	0.035	0.049	
Pork			Sarang et al. (2008)
Top loin	0.564	0.018	
Shoulder	0.527	0.020	
Tenderloin	0.551	0.021	
Beef			Sarang et al. (2008)
Bottom round	0.504	0.019	
Chuck shoulder	0.456	0.023	
Flank loin	0.318	0.038	
Top round	0.472	0.024	
β -Lactoglobulin solution (1 wt%)	0.155	0.0032	Ayadi et al. (2004)
β -Lactoglobulin–xanthan mixture solution (1 wt% protein + 0.2 wt% xanthan gum)	0.156	0.0036	
Deposit from Ohmic heating of β -lactoglobulin solution (1 wt%)	0.058	0.0009	
Deposit from Ohmic heating of β -lactoglobulin–xanthan mixture (1 wt% protein + 0.2 wt% xanthan gum)	0.090	0.0013	

TABLE 6.1 (continued)
Empirical Model’s Parameters for the Prediction of EC of Different Commodities

Material	σ_{25} (s/m)	α (°C) ⁻¹	Reference
Carrageenan			Marcotte (1998)
1%	0.206	0.0046	
2%	0.390	0.0090	
3%	0.470	0.0130	
Xanthan			Marcotte (1998)
1%	0.139	0.0041	
2%	0.250	0.0071	
3%	0.400	0.0090	
Gelatin			Marcotte (1998)
1%	0.062	0.0016	
2%	0.089	0.0024	
3%	0.110	0.0031	
Pectin			Marcotte (1998)
1%	0.047	0.0010	
2%	0.101	0.0021	
3%	0.140	0.0030	
Starch solution			Marcotte (1998)
1%	0.051	0.0013	
2%	0.057	0.0015	
3%	0.069	0.0018	

Note: α is the temperature parameter term from equation.

TABLE 6.2
Linear Model Parameters to Predict EC as a Function of Temperature

Food Material	Treatment	σ_{30} (S/m)	α (°C ⁻¹)	Reference
Carrot	Raw	0.033	0.234	Wang and Sastry (1997)
	Conventional	0.232	0.022	
	OH (After 1 cycle)	0.343	0.021	
	OH (After 2 cycle)	0.763	0.015	
Potato	Raw	0.080	0.218	
	Conventional	0.673	0.021	
	OH (After 1 cycle)	0.576	0.029	
	OH (After 2 cycle)	0.623	0.022	
Yam	Raw	0.034	0.395	
	Conventional	0.380	0.034	
	OH (After 1 cycle)	0.433	0.021	
	OH (After 2 cycle)	0.393	0.023	

Source: Data from Wang, W.-C. and Sastry, S.K. 1997. *Journal of Food Process Engineering* 20:499–516.

Note: $(EC = \sigma_{30} + \alpha T)$ for three vegetables under different Ohmic heating conditions.

of less than 1 and up to over 4 S/m were reported for different solutions, while the temperature changed from room temperature to about 100°C and linear regression models were developed to predict the EC of the solution as a function of temperature. Regression parameters for different hydrocolloid solutions with specific salt concentrations are presented in Table 6.3.

The electrical conductivity of bologna (formulated to contain 20% or 30% fat, and of 4.8% fat ham), containing either 0.7% or 2.3% salt, was measured by Piette et al. (2004) during Ohmic cooking. They did not develop any model for the generated data, while values of 1–6 S/m were obtained for the EC of the tested materials over the temperature range of 15–80°C. They concluded that the EC values of processed meats increased with increasing temperature and salt concentration, while these same values decreased with increasing fat content within the range of the salt and fat contents selected.

The relationship between EC and temperature for apple, sour cherry, and orange juice at different concentrations under different voltage gradients were investigated by Icier and Ilicali (2004) and (2005a). Values of 0.1–1.6 S/m were reported for the three tested fruit juices over the range of the pasteurization temperature (30–80°C), different concentrations (20–60%), and voltage gradients (20–60 V/cm). They found that the apple juice had the lower electrical conductivity for all the concentrations and applied voltage gradient. This was related to the lower acid content of apple juice having a similar insoluble solid content with the sour cherry juice. However, at all the levels of applied voltage gradients, they found an increasing trend in the EC values of the fruit juice with temperature. An individual, simple linear relationship was found between the EC and the temperature for a given concentration and given voltage gradient as follows:

$$EC = C + k T \quad (6.10)$$

TABLE 6.3
Regression Parameters in Linear Models to Predict EC as a Function of Temperature
($\sigma = \sigma_{30} + \sigma(T - 25)$) for Viscose Liquid Foods with Different Salt Concentrations

Type	Salt Concentration (%)	σ_{25} (S/m)	σ (S/m °C)
Carrageenan (1.7%)	0.25	0.848	0.0199
	0.50	1.371	0.0313
	0.75	1.914	0.0413
	1.00	2.173	0.0481
Xanthan (2%)	0.25	0.889	0.0181
	0.50	1.474	0.0305
	0.75	1.969	0.0396
	1.00	2.162	0.0419
Pectin (2.5%)	0.25	0.691	0.0153
	0.50	1.201	0.0261
	0.75	1.690	0.0349
	1.00	2.195	0.0455
Starch (4.3%)	0.25	0.582	0.0123
	0.50	1.066	0.0204
	0.75	1.544	0.0312
	1.00	2.109	0.0427

Source: Data from Marcotte, M., Trigui, M., and Ramaswamy, H.S. 2000. *Journal of Food Processing and Preservation* 24:389–406.

where C and k are the linear regression parameters as intercept and slope for the developed models. These values are presented in Table 6.4 for apple, sour cherry, and orange juices for a given concentration and known voltage gradient. Furthermore, they also developed a more general linear equation over the entire range of applied voltage gradient, but at a given concentration in order to model the EC as a function of temperature, same as Equation 6.10. Slopes and intercepts for the developed models are presented in Table 6.5 for the three juices at a given concentration.

Similarly, Singh et al. (2008) developed the linear regression model again as Equation 6.10 between the electrical conductivity and the temperature for apple, pineapple, orange, and tomato juices at two frequencies of 1 and 10 kHz. The regression parameters of their models are presented in Table 6.6.

TABLE 6.4
Linear Regression Parameters of Electrical Conductivity as a Function of Temperature
($EC = C + kT$) for Apple, Sour Cherry, and Orange Juices at Given Voltage Gradients
and Solid Concentrations

Voltage Gradient (V/cm)	Concentration (%)	Apple Juice ^a		Sour Cherry Juice ^a		Orange Juice ^b	
		Slope	Intercept	Slope	Intercept	Slope	Intercept
60	20	0.0122	0.0300	0.0293	-0.0554	0.0199	-0.0781
	30	0.0162	-0.0127	0.0342	-0.2032	0.0179	-0.0270
	40	0.0145	-0.1728	0.0288	-0.1855	0.0141	-0.0027
	50	0.0118	-0.2088	0.0266	-0.3455	0.0106	-0.0399
	60	0.0097	-0.1645	0.0216	-0.4272	0.0093	-0.0736
50	20	0.0125	0.0141	0.0290	-0.1012	0.0207	-0.0151
	30	0.0142	-0.0585	0.0275	-0.0114	0.0197	-0.0742
	40	0.0128	-0.1250	0.0278	-0.1812	0.0140	-0.0212
	50	0.0111	-0.1842	0.0243	-0.2955	0.0106	-0.0506
	60	0.0087	-0.1426	0.0193	-0.3492	0.0109	-0.0946
40	20	0.0112	0.0669	0.0202	0.2479	0.0187	0.0397
	30	0.0135	-0.0474	0.0223	0.1503	0.0183	-0.0373
	40	0.0136	-0.1497	0.0269	-0.1526	0.0184	-0.1338
	50	0.0105	-0.1701	0.0231	-0.2352	0.0135	-0.1558
	60	0.0079	-0.1329	0.0185	-0.3401	0.0121	-0.2152
30	20	0.0108	0.0458	0.0160	0.3861	0.0105	0.1603
	30	0.1250	-0.0159	0.0190	0.2496	0.016	0.0562
	40	0.0130	-0.1363	0.0227	-0.0518	0.0159	-0.0406
	50	0.0091	-0.1266	0.0228	-0.2405	0.0131	-0.1562
	60	0.0089	-0.1628	0.0165	-0.2741	0.0106	-0.1381
20	20	0.0108	0.0711	0.0177	0.3357	0.0153	0.1608
	30	0.0124	-0.0043	0.0173	0.2696	0.0201	-0.0515
	40	0.0114	-0.0732	0.0224	-0.0086	0.0168	-0.0854
	50	0.0090	-0.1155	0.0206	-0.1718	0.0135	-0.1759
	60	0.0081	-0.1425	0.0151	-0.2407	0.0120	-0.1208

Source: ^aData from Icier, F. and Ilicali, C. 2004. *Journal of Food Process Engineering* 27:159–180. ^bData from Icier, F. and Ilicali, C. 2005a. *European Food Research and Technology* 220:406–414.

TABLE 6.5

Linear Regression Parameters for EC as a Function of Temperature for Apple, Sour Cherry, and Orange Juices at a Given Concentration Valid for Voltage Gradient Ranging from 20 to 60 V/cm ($EC = C + kT$)

Concentration (%)	Apple Juice ^a		Sour Cherry Juice ^a		Orange Juice ^b	
	Slope	Intercept	Slope	Intercept	Slope	Intercept
20	0.0109	0.0641	0.0176	0.3416	0.0158	0.416
30	0.0127	−0.0113	0.0183	0.2702	0.0188	−0.0301
40	0.0123	−0.1042	0.0235	−0.0455	0.0162	−0.0645
50	0.0094	−0.1286	0.0218	−0.2051	0.0129	−0.1442
60	0.0083	−0.1399	0.160	−0.2615	0.0117	−0.1521

Source: ^aData from Icier, F. and Ilicali, C. 2004. *Journal of Food Process Engineering* 27:159–180. ^bData from Icier, F. and Ilicali, C. 2005a. *European Food Research and Technology* 220:406–414.

TABLE 6.6

Linear Regression Parameters for EC as a Function of Temperature for Apple, Pineapple, Orange, and Tomato Juices at Two Frequencies ($EC = C + kT$)

Juice	Frequency (kHz)	Slope ($\times 10^{-3}$)	Intercept ($\times 10^{-3}$)
Apple	1	0.145	1.363
	10	0.176	1.701
Pineapple	1	0.169	1.686
	10	0.181	1.798
Orange	1	0.175	1.206
	10	0.171	1.867
Tomato	1	0.263	1.985
	10	0.247	3.335

Source: Data from Singh, S.P., Tarsikka, P.S., and Singh, H. 2008. *Journal of Food Science and Technology* 45(4):371–372.

6.3 ELECTRICAL CONDUCTIVITY: VOLTAGE GRADIENT DEPENDENCY

In the Ohmic heating process, heat is generated instantly inside the food. The amount of heat generated is directly related to the current induced by the voltage gradient in the field, and the electrical conductivity of the material being heated (Sastry and Li, 1996). Initially researchers applied a constant voltage to evaluate the EC of foodstuffs. Halden et al. (1990) studied the Ohmic heating of pork, pork fat, potato, carrot, and vegetables immersed in brine solution at a constant voltage gradient of 10.87 V/cm. They found that the electrical conductivity changed linearly with temperature. Palaniappan and Sastry (1991a) applied a higher voltage gradient of 60 V/cm to potato, carrot, chicken, and lean beef samples and reported a decrease in the EC as voltage gradient decreased. Yongsawatdigul et al. (1995b) found that the EC of surimi increased with the temperature, the amount of added salt, and moisture content; while voltage gradients did not affect the EC. Values of 1–12 S/m were reported for the EC of surimi containing 1–4% salt concentration and 75–84% moisture content while heating from 10°C to 90°C and different voltage gradients were applied

(3.3–13.3 V/cm). Simple linear regression models were developed for the EC of surimi as a function of temperature for a given applied voltage gradient. Model parameters for the given conditions are given in Table 6.7.

Castro et al. (2003) found that the EC generally increased linearly with an increase in field strength, while testing fresh strawberry and strawberry-based products with different degree of solids content. For most of the products tested, it was found that the field strength does not greatly affect EC, which is in turn significantly different from product to product. An increase of the EC with field strength was obvious for fresh strawberries and strawberry jelly but not for strawberry pulp. Very low values of EC (<0.005 S/cm) were reported for strawberry-based products while the voltage gradient varied from 30 to 100 V/cm. They concluded that even with a higher solids content (>20% w/w) and sugar content over 40°Brix, electrical conductivity is low enough to necessitate the use of a different Ohmic heater design.

The effect of the voltage gradient on the EC of fruit juices was studied by Icier and Ilicali (2004, 2005a). The regression models to predict the values of EC as a function of temperatures were presented in the previous section for different applied voltages. The same authors, in another study (2005b) also reported values of EC as affected by the voltage gradient for tylose and minced beef products. Tylose (sodium carboxy methyl cellulose) is a food model for lean beef that has been used in freezing and thawing research since it has similar thermo-physical properties to lean beef. Five different voltage gradients in the range of 10–50 V/cm, at 50 Hz a.c. were applied in their study while temperatures varied from 30°C to 60°C. Values of EC were reported to be 0.5 – 1.5 S/m for the tested material over the range of the study. Simple linear models, similar to Equation 6.10, were proposed for the predicting EC as a function of temperature at a given voltage gradient for

TABLE 6.7

Estimated Parameters in Linear Model ($EC = C + kT$) for Prediction of EC as a Function of Temperature for Pacific Whiting Surimi Paste at a Given Percentage of MC, Salt Concentration and Specific Voltage Gradient

Moisture (%)	Salt (%)	Voltage Gradient (V/cm)					
		3.3		6.7		13.3	
		Slope	Intercept	Slope	Intercept	Slope	Intercept
75	1	0.030	0.540	0.030	0.606	0.028	0.649
	2	0.052	1.099	0.049	1.204	0.050	1.267
	3	0.074	1.704	0.067	1.904	0.069	1.921
	4	0.092	2.264	0.090	2.533	0.104	2.160
78	1	0.033	0.613	0.031	0.645	0.029	0.696
	2	0.053	1.257	0.051	1.326	0.051	1.449
	3	0.080	1.653	0.072	1.869	0.087	1.894
	4	0.099	2.285	0.096	2.651	0.100	2.709
81	1	0.032	0.629	0.031	0.682	0.029	0.767
	2	0.058	1.327	0.054	1.381	0.057	1.499
	3	0.083	1.933	0.076	2.239	0.082	1.984
	4	0.112	2.540	0.110	2.556	0.131	2.404
84	1	0.036	0.678	0.034	0.758	0.032	0.832
	2	0.060	1.433	0.057	1.623	0.056	1.708
	3	0.074	2.006	0.081	2.433	0.088	2.418
	4	0.092	3.343	0.107	3.495	0.106	3.051

Source: Data from Yongsawatdigul, J., Park, J.W., and Kolbe, E. 1995. *Journal of Food Science* 60(5):922–925.

two minced beef products containing low and high fat component as well as two food models containing 0.5% and 0.67% salt content. The intercept and slope of the models are summarized in Table 6.8. Since their experimental EC data, only the minced beef products showed a nonlinear trend with increasing temperature, so a nonlinear equation as in Equation 6.11 was used to fit the experimental data.

$$EC = A1 T^N + A2 \quad (6.11)$$

Nonlinear regression coefficients for the above-mentioned study are given in Table 6.9.

In another study, Icier and Ilicali (2005c) studied the EC of apricot and peach purees by applying voltage gradients in the range of 20–70 V/cm using a laboratory-scale static Ohmic heating device. Values of 0.5–1.3 S/m were obtained for the tested fruit puree while heating from room temperature to 60°C. The voltage gradient was statistically significant on the Ohmic heating rates for both purees ($P < 0.05$). They found that EC was dependent on ionic concentrations and pulp content and the EC of the fruit purees increased with temperature rise, linearly. The rate of change of temperature for the apricot puree was higher than the peach puree at all voltage gradients applied.

The linear temperature-dependent EC relations were obtained the same as Equation 6.10. Linear regression parameters for the prediction of EC as a function of temperature for peach and apricot puree were presented in Table 6.10 for a given voltage gradient. They have reported that the

TABLE 6.8
Linear Regression Parameters to Predict EC as a Function of
Temperature ($EC = C + kT$) at a Given Voltage Gradient for Minced
Beef and Tylose

Food Samples	Voltage Gradient (V/cm)	Slope	Intercept
Minced beef (low-fat content)	10	0.0118	0.4880
	20	0.0164	0.2698
	30	0.0159	0.2816
	40	0.0173	0.3339
	50	0.0153	0.4200
Minced beef (high fat content)	10	0.0133	0.2598
	20	0.0117	0.2675
	30	0.0132	0.1790
	40	0.0125	0.2768
	50	0.0158	0.2580
Tylose (with 0.5% salt content)	10	0.0181	0.0338
	20	0.0182	0.0495
	30	0.0141	0.2284
	40	0.0167	0.0734
	50	0.0160	0.2450
Tylose (with 0.67% salt content)	10	0.0173	0.2151
	20	0.0219	0.0948
	30	0.0160	0.2500
	40	0.0208	0.1316
	50	0.0200	0.3949

Source: Data from Icier, F. and Ilicali, C. 2005b. *Journal of Food Engineering* 69:67–77.

TABLE 6.9
Nonlinear Regression Parameters as a Function of Temperature ($EC = A_1 T^n + A_2$) to Estimate the EC of Minced Beef Products at a Given Voltage Gradient

Minced Beef Samples	Voltage Gradient (V/cm)	A_1	n	A_2
Low-fat content	10	0.871	0.241	-1.153
	20	1.026	0.250	-1.687
	30	1.236	0.234	-2.005
	40	1.837	0.261	-3.425
	50	1.082	0.241	-1.595
High-fat content	10	0.657	0.287	-1.088
	20	0.802	0.251	-1.285
	30	0.727	0.278	-1.313
	40	1.201	0.210	-1.828
	50	1.023	0.246	-1.638

Source: Data from Icier, F. and Ilicali, C. 2005b. *Journal of Food Engineering* 69:67–77.

predictions of the mathematical model using obtained EC equations were found to be very accurate and their mathematical models can be used to predict the Ohmic heating times for the pasteurization process of fruit purees.

Pongviratchai and Park (2007) studied the effect of voltage gradient (4.3 and 15.5 V/cm) and frequencies (5 Hz to 20 kHz) on the EC of Alaska pollock surimi mixed with native and pre-gelled potato starch at different concentrations (0%, 3%, and 9%) and different moisture contents (75% and

TABLE 6.10
Linear Regression Parameters of Electrical Conductivity as a Function of Temperature ($EC = kT + C$) for Peach and Apricot Puree at Given Voltage Gradient

Voltage Gradient (V/cm)	Peach Puree ^a		Apricot Puree ^a	
	Slope	Intercept	Slope	Intercept
General	0.0096	0.2711	0.0160	0.3040
70	0.0099	0.2515	0.0137	0.3966
65	0.0038	0.5034	0.0149	0.3323
60	0.0111	0.2648	0.0165	0.2714
55	0.0112	0.2043	0.0149	0.3378
50	0.0105	0.2640	0.0114	0.4284
45	0.0118	0.2073	0.0129	0.2757
40	0.0111	0.2218	0.0159	0.3644
35	0.0115	0.2184	0.0163	0.3010
30	0.0108	0.2449	0.0158	0.3185
27.5	0.0098	0.2492	0.0142	0.3461
25	0.0100	0.2367	—	—
22.5	0.0096	0.2348	0.0179	0.2721
20	0.0093	0.2683	0.0153	0.3369

Source: ^aData from Icier, F. and Ilicali, C. 2005c. *Food Research International* 38:1135–1142.

TABLE 6.11

Estimated Parameters for the Correlations of EC as a Function of Temperature at a Given Ohmic Heating Condition (Frequency and Voltage Gradient) for Different Surimi–Starch Paste Modeled

Moisture (%)	Cooking Method	Control		3N ^a		3P		9N		9P	
		Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept	Slope	Intercept
75	55 Hz 60 V	0.053	1.004	0.053	1.113	0.054	1.025	0.049	1.218	0.055	1.916
	5 kHz 60 V	0.054	1.081	0.051	1.132	0.056	1.065	0.051	1.258	0.054	1.976
	20 kHz 60 V	0.057	1.246	0.052	1.870	0.054	1.304	0.047	1.409	0.053	1.290
	5 kHz 220 V	0.053	1.302	0.52	1.197	0.021	1.223	0.050	1.276	0.051	1.124
	20 kHz 220 V	0.049	1.674	0.050	1.600	0.048	1.528	0.050	1.610	0.051	1.465
81	55 Hz 60 V	0.056	1.259	0.057	1.432	0.057	1.166	—	—	0.058	1.016
	5 kHz 60 V	0.058	1.274	0.055	1.382	0.058	1.269	0.050	1.273	0.058	1.116
	20 kHz 60 V	0.057	1.499	0.054	1.533	0.057	1.312	0.053	1.547	0.058	1.207
	5 kHz 220 V	0.060	1.441	0.062	1.299	0.057	1.323	0.055	1.545	0.056	1.245
	20 kHz 220 V	0.055	1.886	0.055	1.751	0.054	1.612	0.052	1.733	0.052	1.615

Source: Data from Pongviratchai, P. and Park, J.W. 2007. *Journal of Food Science* 72(9):E503–E507.

^a N and P stands for native and pregelated potato starch and numbers (3 and 9) show their percentage in the paste.

81%) using a multifrequency Ohmic heating system. Values of 1–6 S/m were reported for the EC of surimi–starch food samples and it was concluded that EC increased as moisture content, applied frequency, and applied voltage increased; however EC decreased with the increase of starch concentration. They have also mentioned that the EC pattern (magnitude) changed when the temperature increased, which was clearly seen in the native potato starch samples after 55°C, especially at high concentrations. Eventually, EC was correlated linearly with temperature, the same as Equation 6.10 for tested surimi-based food samples. The estimated model parameters for the given conditions are in Table 6.11.

6.4 ELECTRICAL CONDUCTIVITY: SOLID CONTENT DEPENDENCY

In spite of temperature, voltage gradient and frequency, other factors related to the product such as size, shape, percentage, and the orientation of the solid content in the electrical field, which basically affects the overall resistance of the system. Limited publications are available for a better understanding of these factors, while only a few of them attempt to model just the solid content.

For tomato (without salt addition) and orange juices, Palaniappan and Sastry (1991b) proposed the following equation to correlate the electrical conductivity at a given temperature (σ_T in S/m) with temperature (T in °C) and solid content of the juices (S).

$$\sigma_T = s_{\text{ref}}(1 + \alpha(T - T_{\text{ref}})) - \beta S \quad (6.12)$$

where T_{ref} is the reference temperature (25°C), σ_{ref} is the conductivity of juices at the reference temperature, α and β are the constant regression parameters obtained as 0.863, 0.174, and 0.101 for tomato and 0.567, 0.242, and 0.036 for orange juices, respectively.

Concerning solid content, the EC of strawberry products was studied by Castro et al. (2003) using two different strawberry-based formulas containing different particle sizes (average cubic

TABLE 6.12

Constant Parameters for the Quadratic Regression Model to Predict the EC of Two Strawberry-Based Formulations as a Function of Temperature at a Given Percentage of Solid Content (°Brix)

Brix (20°C)	Formulation 1			Brix (20°C)	Formulation 2		
	A	B	C		A	B	C
14.5	3×10^{-7}	3×10^{-5}	0.0017	26.5	3×10^{-7}	7×10^{-5}	0.0012
22.5	3×10^{-7}	2×10^{-5}	0.0013	31.5	2×10^{-7}	6×10^{-6}	0.0009
26.5	2×10^{-7}	2×10^{-5}	0.0014	37.5	2×10^{-7}	3×10^{-6}	0.0007
30.5	4×10^{-7}	7×10^{-6}	0.0010	45.5	2×10^{-7}	-1×10^{-6}	0.0006
37.5	3×10^{-7}	1×10^{-5}	0.0008	54.1	3×10^{-7}	-1×10^{-5}	0.0004
41.0	2×10^{-6}	-8×10^{-5}	0.0016	59.5	1×10^{-7}	-5×10^{-6}	0.0002

Source: Data from Castro, I. et al. 2003. *Journal of Food Process Engineering* 26:17–29.

Note: A, B, C are constants of the quadratic regression model equation ($EC = AT^2 + BT + C$).

particle size of 6.4 and 7.9 mm) and six different solid concentrations for each formulation (14.5–41 and 26.5–59.5°Brix). Their results indicated that the presence of sugar suppressed the conductivity of strawberry pulp, as was expected to happen considering that a component such as sugar (being nonionic constituent) causes a decrease in electrical conductivity, as pointed by Sastry (1992). Therefore, regardless of particle size distributions, the EC decreased with the increase of solids content, which they presumed is due to the increase of the resistance for ionic movement. A maximum of a 30% decrease in the EC with increasing particle sizes was reported for the same percents of solids content, which indicates that the resistance of ionic movement may be reduced by smaller particles. Quadratic empirical regression models as a function of temperature in the following equation were developed to predict the EC of specific strawberry-based formulas at a given degree of Brix; indicating the solid percentage of the formulation.

$$EC = AT^2 + BT + C \quad (6.13)$$

Constant values in Equation 6.13 for two different strawberry-based formulations and a given solid content are provided in Table 6.12.

6.5 ELECTRICAL CONDUCTIVITY: MULTIREGRESSION MODELS

It is understood that EC is a material physical property that can be affected by many parameters and having a good estimation of this value definitely can improve the product quality in the Ohmic heating process. In the previous sections, the result of many workers who evaluated this property for different foodstuffs were classified and the proposed empirical equations that correlate EC as a function of single factor, temperature, voltage gradient, and solid content, were presented. However, general and multivariable models are more useful to predict the EC of foods that undergo the Ohmic heating process since EC is a multifactor-dependent material property. Therefore, attempts have been made to simulate the EC as a function of different influencing factors. Some of the existing multiregression models will follow. It is worth mentioning that such models are applicable and valid for a given range of the variable parameters.

The values of EC (1–12 S/m) were reported by Yongsawatdigul (1995b) for Pacific whiting surimi paste. Also, simple linear regression models of EC as a function of temperature were already presented in the previous tables and sections. They have shown that the EC of surimi increased with

temperature and salt content and slightly increased with moisture content. Analyzing all data, they have developed a more general equation for the prediction of EC of the tested materials as presented below:

$$\sigma = 0.1168 + 0.0083T - 2.5115N + 0.0385MN + 0.0229TN + 0.0282N^2 \quad (6.14)$$

where σ is the electrical conductivity (S/m), N the salt content (%w/w), M is the moisture content (% wet basis), T the temperature. This equation could be useful for modeling purposes in the Ohmic heating process of surimi products over the range of the experimental conditions, in this case moisture contents (75–84%), added salt (1–4%), and temperature (10–90°C). This empirical model predicted EC values for surimi paste 16% more than the experimental data.

Wu et al. (1998) studied the EC of Pacific whiting surimi paste using a multifrequency Ohmic heating system (30 Hz–1 MHz) that could deliver 250 DC watts. They found that temperature and salt concentration in the paste had a significant effect on the values of DC electrical conductivity and the EC increased with temperature and salt concentration. They have developed the following regression model to simulate the DC electrical conductivity of Pacific surimi paste as a function of temperature and salt concentration:

$$\sigma_{dc} = -0.0337 + 0.026T + 57.89S + 2.433TS \quad (6.15)$$

where σ_{dc} is the DC electrical conductivity (S/m), T is the temperature (°C), and S is the salt concentration (w/w). The equation is valid for the temperature and salt concentration ranging 20–70°C and 1–3% (w/w), respectively. Positive coefficients of temperature and salt concentration in the model indicate that both the temperature and the concentration have increasing effect on the values of EC. Similar interpretation can be made for their interaction effect meaning that the EC of the paste would increase with temperature at any level of salt concentration.

Moura et al. (1999) measured the EC of tangerine, pineapple, and lemon juices at various concentrations (10–55°Brix) in a temperature range from 20°C to 80°C. They related the EC of the juices to their concentration (°Brix) and temperature. Their results indicated an increase in the EC with increasing concentration up to approximately 30°Brix, and thereafter it started to decrease. Since the increase of concentration increases the viscosity of the juices, which in turn decrease the mobility of the ions, they related this decrease to the increase of the concentration. To simulate the EC as a function of both concentration of the juice (when <45°Brix) and temperature, they have developed and proposed the following exponential Equation 6.16:

$$s = A1 \cdot \text{Brix}^N \cdot \exp(-E_{a0} \exp(A2 \cdot \text{Brix})/RT) \quad (6.16)$$

where σ is the EC of the juice (S/m), R is the gas constant (J/gmol K), T is the temperature (K), E_{a0} is the activation energy (kJ/gmol K), $A1$, N , and $A2$ are constant parameters of the equation which were determined and provided in Table 6.13.

Marcotte et al. (2000) evaluated the EC of four selected hydrocolloid solutions (starch, 4.3%; carrageenan, 1.7%; xanthan, 2%; and pectin, 2.5%) with varying amounts of salt concentration (NaCl ranged from 0.25% to 1%) while a constant voltage of 150 V was applied in a static Ohmic heating cell and heated from 25°C to 80°C. Values of 0.5–5.5 S/m were reported for the tested solutions while they realized that at low salt concentration, carrageenan and xanthan had the shortest heating times and highest ECs. This was followed by pectin. Starch was the least effective, having slowest heating rates and lowest ECs. They also showed that salt content, temperature, and the interaction between salt content and temperature had a significant effect on the EC of all hydrocolloids. Multiple regression models were then proposed as follows:

$$\sigma = A(S) + B(T) + C(S \cdot T) \quad (6.17)$$

TABLE 6.13
Constant Values in the Exponential Equation 6.16 Which Is
Correlating EC as a Function of Concentration and Temperature
for Tangerine, Pineapple, and Lemon Juices

Juice	A1	N	A2	E ₀
Tangerine	4.42303	1.314059	0.0082	12.64
Pineapple	2.56776	1.449332	0.0095	12.06
Lemon	2.95667	1.476278	0.0105	11.51

Source: Data from Moura, S.C.S.R., Vitali, A.A., and Hubinger, M.D. 1999. *Brazilian Journal of Food Technology* 2(1, 2):31–38.

where σ is the EC of the hydrocolloid solution (S/m), S is the salt concentration (%), T is the temperature (°C), and $S \cdot T$ is the interaction variable. Constant values of A , B , and C for different solutions are listed in Table 6.14.

Icier and Ilicali (2004) developed a nonlinear equation as given in Equation 6.18 for the prediction of the EC of apple and sour cherry juices as a function of the influencing parameter in their study over the entire range of the investigated parameters: temperature (30–60°C), solid concentration (20–60%), and applied voltage gradient (20–60 V/cm).

$$s = A1 \cdot (C)^{N1} + A2 \cdot (\Delta V)^{N2} + A3 \cdot T + A4 \quad (6.18)$$

where σ is the electrical conductivity (S/m), C is the solid concentration in the juice (%), ΔV is the voltage gradient applied (V/cm), and T is the temperature (°C). The values of constants parameters ($A1$, $A2$, $A3$, $N1$, and $N2$) in the developed regression models for the two juices are provided in Table 6.15.

Icier and Ilicali (2004, 2005a) also developed another Equation 6.19 which simulates EC as a function of temperature and voltage gradient over the given ranges as mentioned above for fruit juice (apple, sour cherry, and orange) but only at a given concentration.

$$s = A1 \cdot (\Delta V)^N + A2 \cdot T + A3 \quad (6.19)$$

TABLE 6.14
Constant Values in Equation 6.17 for the Prediction of EC of
Selected Hydrocolloids as a Function of Salt Concentration
and Temperature

Type	Estimated Parameters		
	A	B	C
Carrageenan 1.7%	1.080	0.014	0.034
Xanthan 2.0%	1.150	0.013	0.033
Pectin 2.5%	1.040	0.009	0.034
Starch 4.3%	1.010	0.002	0.042

Source: Data from Moura, S.C.S.R., Vitali, A.A., and Hubinger, M.D. 1999. *Brazilian Journal of Food Technology* 2(1, 2):31–38.

TABLE 6.15
Empirical Constants of General EC Equation 6.18 for Fruit Juices

Juice Type	A1	N1	A2	N2	A3	A4
Apple	-3.19×10^{-4}	1.771	5.92×10^{-6}	2.225	0.010	0.187
Sour cherry	-2.11×10^{-7}	3.663	0.008	0.731	0.019	0.202

Source: Data from Icier, F. and Ilicali, C. 2004. *Journal of Food Process Engineering* 27:159–180.

where σ is the electrical conductivity, ΔV is the voltage gradient applied (V/cm), T is the temperature ($^{\circ}\text{C}$), $A1$, $A2$, $A3$, and N are constant parameters which are provided in Table 6.16.

The same authors, in another study (Icier and Ilicali, 2005c) reported values of 0.5–1.3 S/m for fruit puree product (apricot and peach) by applying voltage gradients and temperature in the range of 20–70 V/cm and 30–60 $^{\circ}\text{C}$, respectively, and simulated EC as a function of ΔV and T same as Equation 6.19. They have found that the voltage gradient was statistically significant on the Ohmic heating rates for both purees ($P < 0.05$). Constant parameters for the above equation for fruit puree are given in Table 6.17.

Assiry et al. (2006) reported values of EC for the edible salt (NaCl) solution ranged from 6.2 mS/cm up to about 19 mS/cm depending on the temperature level (40–80 $^{\circ}\text{C}$) and NaCl content (0.25–1.0%, w/w) of the buffer solution. They found that the EC of salt solution could be related to temperature and salt content by the following equation:

$$\sigma = -7.05 + 0.164T + 11.6S \quad (6.20)$$

where S is a percentage of the NaCl concentration (w/w) and T is the temperature ($^{\circ}\text{C}$).

TABLE 6.16
Constant Values in Equation 6.19 Which Simulates EC of Apple, Sour Cherry, and Orange Juices at a Given Concentration as a Function of Temperature and Voltage Gradient

Juice Type	Concentration (%)	A1	N	A2	A3
Apple	20	3.97×10^{-8}	3.422	0.011	0.042
	30	1.84×10^{-8}	3.667	0.013	-0.037
	40	2.586	0.015	0.013	-0.825
	50	5.66×10^{-7}	2.781	0.010	-0.142
	60	2.67×10^{-8}	3.514	0.008	-0.156
Sour cherry	20	4.07×10^{-8}	3.492	0.018	0.315
	30	0.071	0.459	0.019	-0.100
	40	1.53×10^{-5}	2.153	0.024	-0.098
	50	10.854	0.006	0.022	-11.303
	60	0.579	0.100	0.016	-1.067
Orange	20	7.141	0.003	0.016	-7.082
	30	-25.385	0.003	0.018	25.678
	40	-5.42×10^{-8}	3.376	0.016	-0.045
	50	-1.01×10^{-8}	3.346	0.013	-0.144
	60	-22.284	0.004	0.012	22.418

Source: Icier, F. and Ilicali, C. 2004. *Journal of Food Process Engineering* 27:159–180; Icier, F. and Ilicali, C. 2005a. *European Food Research and Technology* 220:406–414.

TABLE 6.17
Empirical Constants of General EC Equation 6.19 for Fruit Puree

Puree Type	A1	N	A2	A3
Apricot	-3.432	0.017	0.015	3.963
Peach	11.878	0.004	0.010	-11.793

Source: Data from Icier, F. and Ilicali, C. 2005c. *Food Research International* 38:1135–1142.

6.6 EFFECTIVE ELECTRICAL CONDUCTIVITY MODELS

Several modeling studies have been presented that simulate effective thermal conductivity (ETC) of multicomponent materials (Brailsford and Major, 1964; Rocha and Cruz, 2001; Maroulis et al., 2002; Buonanno et al., 2003; Wang et al., 2006, 2008; Côté and Konrad, 2009; Zhu et al., 2010). For the ETC calculation of two-component material systems, five basic structure models have been proposed as: parallel, series, solid particles in continuous liquid (Maxwell–Eucken 1), and liquid in continuous solid (Maxwell–Eucken 2), and effective medium theory (EMT) conditions (Landauer, 1952; Maxwell, 1881; Rocha and Cruz, 2001; Buonanno et al., 2003). Assuming the similarity between thermal and electrical conductivity phenomena, the principle approach of the ETC modeling studies can also be applied in the effective modeling of electrical conductivity (EEC) of particle–fluid food mixtures.

The theoretical models of the five basic structures for two-component (solids and fluid) food systems are presented in Equations 6.21 through 6.25.

Parallel case:

$$s = f_L s_L + f_S s_S \quad (6.21)$$

Series case:

$$s = \frac{1}{f_L / s_L + f_S / s_S} \quad (6.22)$$

Maxwell–Eucken 1:

$$s = \frac{f_L s_L + f_S s_S (3s_L / (2s_L + s_S))}{f_L + f_S (3s_L / (2s_L + s_S))} \quad (6.23)$$

Maxwell–Eucken 2:

$$s = \frac{f_L s_L (3s_S / (s_L + 2s_S)) + f_S s_S}{f_L (3s_S / (s_L + 2s_S)) + f_S} \quad (6.24)$$

EMT:

$$f_L \frac{s_L - s}{s_L + 2s} + f_S \frac{s_S - s}{s_S + 2s} = 0 \quad (6.25)$$

where σ is the overall electrical conductivity of the system, f is the volume fraction, L is a subscript for liquid, and S is a subscript for solid.

For Ohmic heating of particulate foods, the most common case is solid particles dispersed in continuous liquid phase (Maxwell–Eucken-1). Parallel, Series, and Maxwell–Eucken-2 structures may not be very practical and applicable in Ohmic heating applications. These basic models are presented here just for comparison and better understanding of the fundamentals of the model structure systems.

A general form of the above-mentioned models was proposed by Wang et al. (2006) as the following Equation 6.26:

$$\mathbf{s} = \frac{\sum_{i=1}^N f_i \mathbf{s}_i (d_i \mathbf{s}_c / ((d_i - 1) \mathbf{s}_c + \mathbf{s}_i))}{\sum_{i=1}^N f_i (d_i \mathbf{s}_c / ((d_i - 1) \mathbf{s}_c + \mathbf{s}_i))} \quad (6.26)$$

where N is the number of material components in the food matrix, f_i is the volume fraction of i th component, σ_i is the electrical conductivity of component i , d_i is shape/size factor (dimensionless); σ_c is the electrical conductivity of the continuous phase.

Equations 6.21 through 6.25 can be derived from Equation 6.26 by suitable selection of the parameters d_i and σ_c . For example, the parallel model can be obtained when $d_i \rightarrow \infty$ or $\sigma_c = \sigma_i$; the series model can be derived when $d_i = 1$, or $\sigma_c \rightarrow 0$; the Maxwell–Eucken equations can be obtained when $d_i = 3$ and $\sigma_c =$ electric conductivity of the continuous phase (solid or liquid); and the effective medium theory (EMT) can be derived when $d_i = 3$ and $\sigma_c = \sigma$.

For a food mixture containing a carrier fluid and different types of solid components, the effective electrical conductivity values could be evaluated using the same model as Equation 6.26. However, the application of this general model to multicomponent food systems depends on the knowledge of the d_i values of different components, which are not available. Furthermore, the d_i factor is related to the sphericity of the dispersed phase (Fricke, 1924; Hamilton and Crosser, 1962) and to the number of Euclidean dimensions of the system (Kirkpatrick, 1973). The most common value recommended in the literature for d_i is 3 (Wang et al., 2006).

Carson et al. (2006) and Wang et al. (2006) applied a modified form of the model originally developed by Krischer (1963) based on the combination of the basic structural models and additional weighting factor (f), also named distribution factor, defined as a structure volume fraction (parallel or series). It is assumed that the series and parallel models define the upper and lower limits for the effective conductivity of any heterogeneous material in which the distribution factor as well as the volume fraction and thermal conductivities of each component are known accurately. Kirscher's model, one of the most widely used, has been used to estimate the effective thermal conductivity of a multicomponent system while it is basically a combination of the prediction of the series and parallel models. The model was formulated as follows:

$$\mathbf{s}_e = \frac{1}{((1 - f/\mathbf{s}_p) + (f/\sigma_{se}))} \quad (6.27)$$

where σ_e is the effective conductivity and f is the volume fraction of parallel or series structure in the system, and σ_p and σ_{se} are the conductivities of the parallel and series portion of the system containing different components which can be calculated as follows:

$$\mathbf{s}_p = \mathbf{f}_1 \mathbf{s}_1 + \mathbf{f}_2 \mathbf{s}_2 + \mathbf{f}_3 \mathbf{s}_3 \quad (6.28)$$

$$\mathbf{s}_{se} = \frac{1}{(\mathbf{f}_1/\mathbf{s}_1) + (\mathbf{f}_2/\mathbf{s}_2) + (\mathbf{f}_3/\mathbf{s}_3)} \quad (6.29)$$

where $\sigma_1, \sigma_2, \sigma_3$ are the conductivities of different components in parallel or series volume, and ϕ_1, ϕ_2, ϕ_3 are the volume fractions of each component.

Although, with such weight, combination models may be useful in some situations; however, the main concern about the application of Kirscher's model is determining the values of the weighting factor, which cannot be determined mechanically from information about the physical structure. These models were used for the simulation of thermal conductivity and could be evaluated and examined for the simulation of effective electrical conductivity of the multicomponent of food matrices as well.

Recently, Zhu et al. (2010) experimented in measuring the electrical conductivity of cubic food particles (carrot, potato, radish, beef muscle, pork muscle, and commercial ham) dispersed in carrier fluid (5% w/w starch–water solution with 0.15–1.5% w/w salt concentrations). They applied the five existing theoretical models (series, parallel, two forms of Maxwell–Eucken models, and the effective medium theory) to evaluate the EC of various solid–fluid food matrixes, and reported that parallel and series models were not practically applicable in the real food system. However, the first Maxwell–Eucken model, which describes solid particles dispersed in continuous liquid, showed the best agreement between predicted EC values and experimental data. The model provides a useful and relatively simple new approach to predict the effective EC for mixtures of different types of solid food particles immersed in liquid food. These models do not contain difficult-to-determine empirical parameters, and effective EC prediction using these models is not complicated and is, therefore, useful in practical applications.

6.7 COMPUTATIONAL PREDICTION MODELS

In the last two decades approaches based on artificial intelligence, such as artificial neural networks (ANNs), support vector machines (SVM) and genetic algorithm (GA), have been introduced for modeling complex systems in different studies. They have the capability of constructing relationships between inputs and outputs using a set of training data, and do not require a prior knowledge of the governing processes (Anderson and Rosenfeld, 1988; Wasserman, 1989; Zornetzer et al., 1990; Gunn, 1998).

The ANN is becoming a promising tool to model the complex systems. It is a computational method based on biological neural networks that mimic the human brain. It involves a network of simple processing elements (neurons) that can exhibit complex global behavior, determined by the connections between the processing elements and element parameters. The key component of this network is the unique information processing system structure. This structure consists of a huge number of processing elements (PE's) that are interconnected and working in unity to solve specific problems. ANNs have a strong capability in establishing nonlinear relationships between dependent and independent variables, and generally can be applied to classification as well as prediction problems. The most commonly used ANN is the multilayer feed-forward neural network, which consists of different layers (input, hidden, and output). The hidden layer enables the ANN to solve nonlinear and complex problems (Masters, 1993). For each processing element, ANN employs a transfer function, which is a nonlinear function and translates the inputs to the potential outputs. The commonly used transfer functions for nonlinear problem is the sigmoid function (Medsker and Liebowitz, 1994). The ANN is a supervised method and, like people, learns from example. Using a set of data (training data set), the ANN model can be developed to solve a specific problem.

The SVM algorithm, a new and innovative method in the field of artificial intelligence, is a supervised learning tool based on the statistical learning theory (Vapnik, 1995) for data mining (Boser et al., 1992; Cortes and Vapnik, 1995). In SVM method, a classification/regression function will be set up by the use of a training data set. The focus of SVM is to minimize a bound on the risk function, rather than minimizing the error in training data, which will be obtained by applying a structural risk minimization (SRM) principle. In SVM linear functions are employed for learning; however, for nonlinear cases, using a so-called kernel technique SVM will plot the data into a higher-dimensional feature space, where linear functions can be applied. One of the main advantages of SVM over other data mining techniques, such as ANNs, is its simplicity. SVMs have emerged in recent times as a popular technique for data analysis, such as tissue classification (Furey

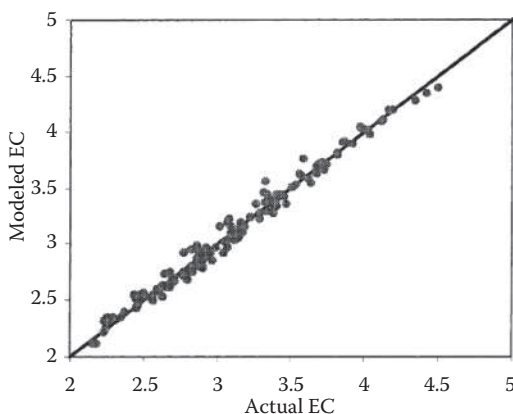


FIGURE 6.1 Comparison of the predicted from ANN and measured electrical conductivity of milk.

et al., 2000; Pavlidis et al., 2004), shape extraction and classification (Cai et al., 2001; Du and Sun, 2004), protein recognition (Zien et al., 2000), bakery process data (Rousu et al., 2003), hyperspectral data (Gualtieri and Crompt, 1998), crop classification (Camps-Valls et al., 2003), and regression problems (Mukherjee et al., 1997; Gunn, 1998; Pontil et al., 1998; Sivapragasam et al., 2001; Gao et al., 2003; Bray and Han, 2004; Karimi et al., 2008).

Computational methods such as SVM and ANN have the ability to predict the electrical conductivity of complex food system by establishing a linear/nonlinear model between electrical conductivity and the other parameters (such as temperature, salt, moisture content, solid content, protein, and fat). In literature, however, very little attention has been made concerning application of such methods for predicting electrical conductivity. Hussain and Rahman (1999) used ANN to predict thermal conductivity of various fruits and vegetables (apples, pears, corn starch, raisins, and potatoes). Considering the fact that the electrical conductivity of milk changes with the variation in temperature and milk components (such as protein, fat, and lactose), it is most likely that a computational method such as ANN can be applied to relate electrical conductivity to those parameters. In this regard, Therdthai and Zhou (2001) used ANN to predict the electrical conductivity of milk samples based on those parameters by employing a multilayer feed-forward artificial network with back-propagation training algorithm. They found that a 4-layer ANN with a log-sigmoid transfer function provided the best ANN model to predict the electrical conductivity of recombined milk. A comparison of the predicted electrical conductivities with the actual data is presented in Figure 6.1. As can be seen from Figure 6.1 the predicted electrical conductivity of milk was well correlated with the measured data. Moreover, the measured electrical conductivities were in the range of 2.15–4.5 mS/cm.

6.8 CLOSING REMARKS

Considerable work on computational modeling has been performed to study the Ohmic heating behavior of food materials. These models mainly simulate the temperature profiles of foodstuff undergoing the Ohmic heating process. Electrical conductivity is one of the most important input parameters for the simulation techniques. This is a material property and is highly temperature dependent. The voltage gradient and frequency of the power supply unit can also affect the values of electrical conductivity. Differences between real values of material properties and estimated ones using proposed models can be expected due to the great variety of biological materials as well as the problems associated with the system parameters while scaling-up for commercial purposes. However, existing models in the literature are very useful tools for an initial evaluation and process design, but cross checking and validating selected models must be verified for a given food formulation and specified unit operation system.

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Section 3

Biological Effects of Electricity on Foods

7 Electricity Effects on Microorganisms and Enzymes

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7.1 HEAT PROCESSING

Several heat processes are applied to foods in a number of different contexts. Today pasteurization and sterilization heat processes are commonly employed in the food industry (Table 7.1) and their main objectives are to eliminate target pathogens associated with the product and to extend the shelf-life of food by reducing or eliminating potential spoilage microorganisms during storage.

Applications of heating processes relying on indirect mechanisms of heat transfer to foods systems are very well established in the food industry today. However, these indirect mechanisms of heating in which heat exchangers (shell-and-tube, scrapped-surface, and plate-and-frame) are commonly employed, are limited by often reduced heat-transfer efficiencies, and consequently, by the time required to transport sufficient heat into the center of the food material, known as the “cold spot,” in order to achieve the desired lethal effect. In most cases, the price of safety and long-term stability of food material is paid in terms of the loss of relevant physical and chemical properties of food products, such as fresh volatile flavors and vitamins.

Having this in mind, the development of Ohmic heating technology for continuous thermal treatment of food systems has a great industrial and scientific interest (Ayadi et al., 2004a, b). Ohmic heating is considered a volumetric form of heating and a HTST (high-temperature short-time) process (De Alwis and Fryer, 1990; Reznick, 1996; Zareifard et al., 2003) in which thermal energy is generated directly inside the food material. This heating pattern leads to a more uniform heating, allowing the reduction of over-processing, and consequently, bringing minimal organoleptic changes to the processed food products. Currently, the discussion is also focused on the application of Ohmic heating for enzyme and microbial control. Inactivation of microorganisms and enzymes are key parameters to be addressed in the production process and the use of novel low-energy or efficient methods of inactivation continue to attract interest (Palaniappan and Sastry, 1992).

TABLE 7.1
Main Heat-Treatment Processes Applied in the Food Industry

Heat Process	Main Objective	Temperature Range (°C)
Cooking (e.g., baking, boiling, frying, and grilling)	Improvement of digestibility and flavor, and destruction of pathogenic microorganisms	≤100
Blanching	Expulsion of oxygen from tissues and inactivation of enzymes	<100
Drying/Concentration	Removal of water to enhance keeping quality	<100
Pasteurization	Elimination of key pathogens and spoilage organisms	60–80
Sterilization	Elimination of microorganism to achieve commercial sterility	≥100

Source: Adapted from Adams, M. and Moss, M. 1995. *Food Microbiology*. London: The Royal Society of Chemistry.

7.2 INACTIVATION EFFECTS

7.2.1 THE BASICS

The thermal inactivation of a homogeneous microbial population (or of a solution containing it) is considered to be logarithmic, which is equivalent to a first-order chemical reaction, and can therefore be represented by a linear, semi-logarithmic graphic curve. This representation of the decimal logarithm of the surviving microbial, versus time of exposure to a constant temperature, can be described by the equation:

$$\text{Log } N_s = \text{Log } N_0 - \left(\frac{k}{2.303} \right) \cdot t \quad (7.1)$$

where N_s is the number of microbial survivors after heating treatment, N_0 is the initial microbial population, k is the inactivation constant and t is the time of exposure to lethal conditions.

The principal parameter to evaluate the thermal resistance characteristics of a homogeneous microbial population is the D -value. It represents the time of exposure (at a constant temperature) required to reduce the microbial population by 90% or, in other words, by a logarithmic cycle. The D -value is the negative inverse of the angular coefficient of the survival curve. The temperature interval needed to reduce 90% of the decimal reduction time (D -value) is the so-called z -value and can be calculated from the following equation:

$$\frac{\text{Log } D_2 - \text{Log } D_1}{T_2 - T_1} = \frac{1}{z} \quad (7.2)$$

These kinetic parameters D and z , allow the comparison of different process technologies in terms of their effects on the reduction of microbial counts. Further, the extension of their meaning, for example, to the case of enzyme inactivation is straightforward.

The application of the Ohmic heating technology to the food industry is fully dependent on its validation with experimental kinetic data to evaluate the effects of the moderate electric fields on enzymes, biological tissues and microorganisms. An important step toward such validation is the determination of D and z values for microorganisms and enzymes which are significant for the food processes, such significance being due to their food quality degradation activity or due to their food quality promoting effects.

7.2.2 INACTIVATION OF MICROORGANISMS

The main mechanism of microbial inactivation under Ohmic heating is thermal in nature. However, during Ohmic heating the severity of the thermal treatment required for microbial inactivation in biomaterials and foods could be potentially reduced if there exists any sub-lethal injury or additional lethal effect due to electric current (Palaniappan and Sastry, 1992). This additional nonthermal effect for destruction of microorganisms during Ohmic heating brought by the presence of electricity is still generating some controversy as not much research has been conducted in this field. Most published results concerning the effects of electric fields during Ohmic heating are somehow inconclusive; they either do not refer to the sample temperature or cannot eliminate temperature as a variable (Palaniappan et al., 1990; USA-FDA, 2000).

The results from the application of Ohmic heating to the fermentation by *Lactobacillus acidophilus* (Cho et al., 1996), a lactic bacterium used in the dairy industry, have shown that the fermentation lag phase at 30°C was significantly reduced (18-fold) under low-voltage Ohmic conditions, as compared with a conventional fermentation (Table 7.2). The authors suggested that this effect might be due to the minimization of the inhibitory action of a fresh medium and improved nutrition absorption. This study provides evidence that the Ohmic heating technology may be useful to the dairy industry; for example, it reduces the time for processing yogurt and cheese (Cho et al. 1996).

The inactivation of *Bacillus subtilis* spores by continuous or intermittent Ohmic and conventional heating was studied by Cho et al. (1999) to determine if the presence of an electric field during heating had an additional effect on the inactivation of this microorganism. Experiments were conducted in an Ohmic fermenter for temperatures ranging from 88°C to 99°C. Ohmically heated spores at 92.3°C had a significantly lower decimal reduction time; the *D* value was reduced by 1 min for Ohmic heating when compared to conventional heating by water circulation (Table 7.3). It is possible, therefore, to infer that the microbial inactivation was affected by the incident electric field in the medium during the heating process. Cho et al. (1999) also studied comparatively the effect of single- and double-stage heating. After inoculation, samples were heated conventionally or Ohmically using a single-stage (90°C for 30 min) or double-stage (90°C for 15 min) treatment. In

TABLE 7.2
Growth Parameters for *L. acidophilus* during Fermentations Performed under Ohmic and Conventional Heating

Heating	Fermentation Temperature (°C)	Lag Period (h)	Minimum Generation Time (h)	Minimum Growth (log ₁₀ CFU/mL)
Treatments				
Conventional	30	6.09 ^a	1.03	9.80
Ohmic (at 15 V/cm)		0.34 ^b	1.26	9.69
Ohmic (at 40 V/cm)		1.44 ^b	1.41	9.68
Conventional	35	1.54 ^a	0.56	9.81
Ohmic (at 15 V/cm)		1.56 ^a	0.47	9.70
Ohmic (at 40 V/cm)		0.92 ^a	0.64	9.74
Conventional	40	1.24 ^a	0.37	9.89
Ohmic (at 15 V/cm)		1.85 ^a	0.33	9.82
Ohmic (at 40 V/cm)		1.28 ^a	0.38	9.71

Source: Adapted from Cho, H.-Y., Yousef, A.E., and Sastry, S.K. 1996. *Biotechnology and Bioengineering* 49:334–340.

^{a-b} Means within each data block with the same superscripts letters are not significantly different at *p* = 0.05.

TABLE 7.3

Thermal Inactivation Kinetic Parameters Values for *Bacillus subtilis* Spores under Conventional (Conv.) and Ohmic Heating

Treatment	$D_{88.0^{\circ}\text{C}}$ (min)	$D_{92.3^{\circ}\text{C}}$ (min)	$D_{95.0^{\circ}\text{C}}$ (min)	$D_{99.1^{\circ}\text{C}}$ (min)	z value ($^{\circ}\text{C}$)	E_a (kcal mol $^{-1}$)
Conv.	32.8 ± 2.42	9.87 ± 0.08	5.06 ± 0.41	—	8.74 ± 0.39	70.0 ± 3.16
Ohmic	30.2 ± 2.85	8.55 ± 0.23	—	1.76 ± 0.02	9.16 ± 0.28	67.5 ± 2.02

Source: Adapted from Cho, H., Yousef, A., and Sastry, S. 1999. *Biotechnology and Bioengineering* 62(3):368–372.

case of double-stage heating, the sample was heated and held at 90°C for 15 min, cooled rapidly to 37°C and held at this temperature for 20 min, heated again and held at 90°C for 15 min, and then cooled to 25°C. The authors have observed that double-heating treatment inactivated spores more effectively as compared to single heating, regardless of the heating method; the average increase in inactivation due to double heating was 1.1 log spores/mL and spore inactivation during double-stage treatment was greater for Ohmic than for conventional heating. Ohmic heating showed a greater tyndallization effect, when compared to conventional heating, indicating that the electric field may affect spore germination and may also cause cell (or spore) injury. The dependence on the temperature of the D value (i.e., the z value) and the activation energy (E_a) of the process were not significantly affected, indicating that electricity affects the death rate, but not the temperature dependency of the spore inactivation process. Thus it was concluded, even though spore inactivation during Ohmic heating was primarily due to the thermal effect, there was an additional killing effect caused by the electric current.

Palaniappan and Sastry (1992) found no difference between the effects of Ohmic and conventional heat treatment on the death kinetics of the yeast *Zygosaccharomyces bailii*, under identical heating histories. In some cases, however, a mild electrical pretreatment decreased the subsequent inactivation requirements for *Escherichia coli*. The authors observed only slightly lower D values for the inactivation of *Z. bailii* (Table 7.4) when Ohmic heating was applied at temperatures lower than 56°C. However, the thermal requirement for inactivation was reduced when a sub-lethal electrical treatment was applied, implying that the electric field lowered the heat resistance of microorganisms. Microbial death during Ohmic heating was mainly attributed to thermal effects, while the nonthermal effects were insignificant.

The effect of Ohmic heating on the thermal inactivation of *Byssoschlamys fulva*, an ascospore-producing filamentous fungus, has been studied by Castro et al. (2007). This fungus is highly heat resistant, it may produce an important mycotoxin (patulin), and it has been documented for the spoilage of canned and bottled fruits, especially strawberries (Beuchat and Rice, 1979). The death kinetic parameters for inactivation of *B. fulva* were determined in an industrial strawberry pulp in the temperature range of 85°C to 105°C (see Table 7.5) and °Brix values of 24–37. The D values

TABLE 7.4

Thermal Inactivation Kinetic Parameters, D and z Values, for *Z. baillii*, under Conventional and Ohmic Heating

Treatment	$D_{49.75^{\circ}\text{C}}$ (min)	$D_{52.30^{\circ}\text{C}}$ (min)	$D_{55.75^{\circ}\text{C}}$ (min)	$D_{58.7^{\circ}\text{C}}$ (min)	z Value ($^{\circ}\text{C}$)
Conventional	294.6 ± 6.73	149.74 ± 19.59	42.71 ± 0.57	16.88 ± 0.37	7.19 ± 0.23
Ohmic	274.0 ± 8.14	112.97 ± 1.07	43.11 ± 1.44	17.84 ± 0.09	7.68 ± 0.09

Source: Adapted from Palaniappan, S. and Sastry, S.K. 1992. *Biotechnology and Bioengineering* 39:225–232.

TABLE 7.5
Kinetic Parameters of Thermal Degradation of *Brachypsectra fulva* in Strawberry Pulp (37.0°Brix)

Heating Method	D Values (min)				z Value (°C)
	85°C	90°C	100°C	105°C	
Conventional	12.31 ± 0.10	7.37 ± 0.73	3.73 ± 0.00	3.08 ± 0.29	33.28 ± 0.80
Ohmic	6.50 ± 0.22	4.27 ± 0.09	2.41 ± 0.00	1.83 ± 0.01	37.25 ± 0.10

Source: Adapted from Castro, I. 2007. Ohmic heating as an alternative to conventional thermal treatment. PhD thesis, University of Minho.

obtained under the presence of electric fields were lower than those obtained under conventional heating.

In fact, these data agree with the hypothesis that electricity during Ohmic heating has an additional effect on ascospores inactivation. Statistical results showed that for the conditions tested, the conventional *D* values are significantly different ($p < 0.05$) from the one obtained when using Ohmic heating (Castro et al., 2007). The authors also observed that the *z* value and temperature dependence was similar for both types of treatments when using 14.5 and 24 °Brix samples, but the rise of the °Brix values to 30.5 and 37.0 led to significant differences ($p < 0.05$) between the two types of treatments (Castro et al., 2007).

The *D* and *z* values corresponding to thermal inactivation of spores of *Bacillus licheniformis*, were determined for the Ohmic treatment of cloudberry jam (Pereira et al., 2007). *B. licheniformis* is commonly isolated from fruit preparations and frequently associated with food poisoning (Iurlina et al., 2006). *B. licheniformis* spores in cloudberry jam were subjected to different treatments under similar conventional and Ohmic thermal histories in order to assess if the presence of a moderate electric field (20 V/cm) plays a role in the spore inactivation mechanism. Results have shown that the time required for thermal treatment was reduced with the Ohmic heating treatment, indicating that in addition to the thermal effect the presence of an electric field in Ohmic heating provided a nonthermal killing effect over spores of *B. licheniformis*. The temperature dependency (*z* value) was statistically similar in both types of treatments ($z_{\text{conventional}} = 11.4^{\circ}\text{C}$ and $z_{\text{Ohmic}} = 11.1^{\circ}\text{C}$, see Figure 7.1), indicating that the presence of the electrical current affected the death rate, but did not affect the temperature dependency of the spore inactivation process.

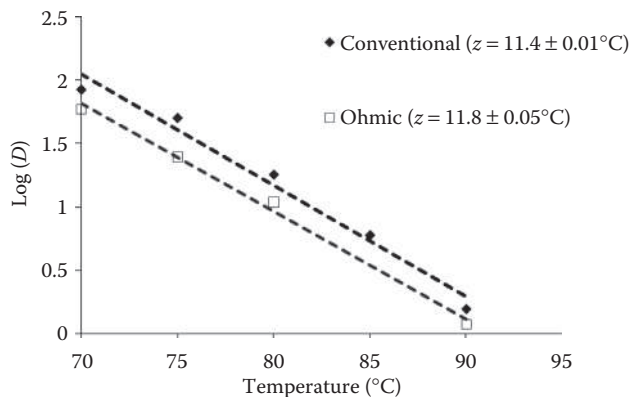


FIGURE 7.1 Death kinetics of the spores of *B. licheniformis* when submitted to Ohmic (open symbols) and conventional (full symbols) heating.

TABLE 7.6

Decimal Reduction Times (*D* values) for Viable Aerobes and *Streptococcus thermophilus* under Conventional and Ohmic Heating

Heating	Viable Aerobes			<i>S. thermophilus</i>		
	<i>D</i> _{57°C} (min)	<i>D</i> _{60°C} (min)	<i>D</i> _{72°C} (min)	<i>D</i> _{70°C} (min)	<i>D</i> _{75°C} (min)	<i>D</i> _{80°C} (min)
Conv.	11.25 ± 1.45 ^a	9.39 ± 0.85 ^a	0.44 ± 0.00 ^a	7.54 ± 0.37 ^a	3.30 ± 0.42 ^a	0.20 ± 0.03 ^a
Ohmic	8.64 ± 1.08 ^b	6.18 ± 0.44 ^b	0.38 ± 0.00 ^b	6.59 ± 0.35 ^b	3.09 ± 0.55 ^a	0.16 ± 0.03 ^b

Source: Adapted from Sun, H-X. et al. 2008. *Food Science and Technology Research* 14(2):117–123.

^{a-b} Means within each data column with the same superscripts letters are not significantly different at *p* = 0.05.

The effects of Ohmic and conventional heating on the thermal inactivation of *E. coli* were studied in milk (Pereira et al., 2007). *E. coli* frequently contaminates dairy products when their manufacturing conditions are unsanitary. The results have shown that, under similar thermal histories, inactivation was faster when the Ohmic heating was applied indicating that, in addition to the thermal effect, the presence of an electric field provided a nonthermal additional killing effect over vegetative cells of *E. coli*.

Milk viable aerobes and *Streptococcus thermophilus* inactivation have been determined by Sun et al. (2008). According to these authors, the results clearly show that both microbial counts and the calculated decimal reduction time (*D* value) resulting from Ohmic heating treatments was significantly lower than those resulting from conventional heating (Table 7.6).

According to Sun et al. (2008) the inactivation effect of electricity is significant when compared to that of heat and was shown to be related to the electrical voltage and frequency.

Overall, the information regarding nonthermal effects provided by electricity during Ohmic heating is still scarce and more research work is required to elucidate the mechanism of the non-thermal effect of electricity on microorganisms, particularly concerning the physiological characteristics of microorganisms, such as changes in the glycosylation degree of proteins and lipids, for example (Vicente et al., 2006).

7.2.3 ENZYME DEGRADATION

The use of enzymes in food processing is widespread once they possess an important role: improvement of food quality (e.g., texture and flavor), recovery of by-products, and achieving higher yields of extraction are just a few examples (Somogyi et al., 1996, van Loey et al., 2002). The control of enzymatic activity is required in many food processing steps in order to promote or inhibit enzymatic activity; enzymes have either negative or positive impacts on food quality attributes, such as production of off-flavors, off-tastes, or changes in rheological properties.

There is still limited information available concerning the effects of moderate electric fields during heating on the activities of relevant enzymes. Castro et al. (2004) have investigated the effects of Ohmic heating on several enzymes, such as lipoxigenase (LOX), polyphenoloxidase (PPO), pectinase (PEC), alkaline phosphatase (ALP), and β-galactosidase (β-GAL), which may play important roles before, during, and after food processing operations or might be used as time–temperature integrators (TTIs). The thermal history of the conventionally and Ohmically processed samples was made similar in order to eliminate temperature as a variable, thus allowing researchers to determine if there was a nonthermal additional effect on the inactivation during Ohmic heating. Results have shown that all the enzymes followed first-order inactivation kinetics for both conventional and Ohmic heating treatments. Moreover, this study demonstrated that the presence of an electric field during heating has an additional effect on LOX and PPO inactivation where much lower *D* values

TABLE 7.7

Thermal Kinetic Inactivation Parameters for Lipoxigenase (LOX), Polyphenoloxidase (PPO) under Conventional (Conv.) and Ohmic Heating

Temperature (°C)	LOX				PPO			
	<i>D</i> Value (min)		<i>z</i> Value (°C)		<i>D</i> Value (min)		<i>z</i> Value (°C)	
	Conv.	Ohmic	Conv.	Ohmic	Conv.	Ohmic	Conv.	Ohmic
60	117.8	6.92	10.83	14.75	—	—		
62	20.44	5.38			—	—		
68	5.43	1.57			—	—		
75	0.99	0.58			61.61	19.37		
78	0.77	0.47			—	—		
80					23.74	6.79	11.85	12.77
85					10.30	3.52		
90					3.15	0.92		
95					1.51	0.58		

Source: Adapted from Castro, I. et al., 2004. *Journal of Food Science* 69:696–701.

where found as compared to conventional heating (Table 7.7). This means that a shorter treatment will be needed for the same inactivation degree, thus reducing negative thermal effects in the quality of food components, such as thermal destruction of vitamins, pigments, and fruit texture. On the other hand, in the case of PEC, ALP, and β -GAL, the electric field seems not to have an influence in enzyme death kinetics, once both heating treatments (conventional and Ohmic) presented identical *D* and *z* values.

The effects of electrical heating on pectin esterase (PE) activity in orange juice were examined and compared with those of heat pasteurization at 90°C for 50 s (Leizerson and Shimoni, 2005). A heating treatment is usually applied to inactivate PE; once this enzyme may cause cloud loss in orange juice by de-esterification of pectin. Results have shown that Ohmic heating reduced PE activity by 90–98% as compared to its activity in fresh orange juice, while under conventional pasteurization conditions, the residual PE activity was reduced by 95%.

Recently, Icier et al. (2006) studied peroxidase (PA) inactivation during Ohmic blanching of pea puree. Peroxidases are considered to be one of the most heat-stable enzymes in vegetables, and their inactivation is usually used to indicate the effectiveness of blanching (Akyol et al., 2004). Results have indicated that inactivation of PA can be performed at a lower processing time than conventional water blanching and that the critical inactivation time has decreased with the increasing voltage during Ohmic blanching (Table 7.8). The authors also observed that Ohmic heating caused less browning than conventional heating.

Much in the same way, the stability of food enzymes used as TTIs was also accessed during Ohmic heating by Wilinska et al. (2006). In this work, the tested enzymes were ALP in dairy products, PE in fruit jams and juice, and PA in vegetable pasta. The kinetic inactivation was studied for temperatures ranging from 52°C to 78°C and, in order to achieve comparable thermal inactivation, the preheating phases of conventional and Ohmic treatment were made equal. The authors have concluded that the presence of an electric field caused enhanced inactivation reducing the time needed for inactivation for all the enzymes tested.

In short, the results regarding enzyme thermal degradation kinetics in the presence of a gradient voltage suggest that the “electric effect” is enzyme-dependant and, therefore, no general behavior or trend was observed. Care should be taken when extrapolating the results obtained for one enzyme

TABLE 7.8
The Inactivation Times of Peroxidase in Pea Purees Blanched Conventionally and Ohmically at Different Electric Fields and Heating Conditions

Blanching	Electric Field (V cm ⁻¹)	Heating Time (s)		
		Come up Time 30°C to 100°C	Holding at 100°C	Critical Inactivation
Ohmic	20	516	60	576
	30	141	60	201
	40	74	30	104
	50	54	0	54
Conventional	—	—	300	300

Source: Adapted from Icier, F., Yildiz, H., and Baysal, T. 2006. *Journal of Food Engineering* 74:424–429.

under a specific set of conditions; for example, the media used for the enzyme activity assays or the food matrix in which the enzyme is being tested differ.

7.3 ADDITIONAL NONTHERMAL EFFECTS

7.3.1 NONTHERMAL EFFECTS ON MICROORGANISMS

In addition to heating, the applied voltage presents the possibility of causing electroporation of the cell membranes. Cell electroporation is defined as the formation of pores in cell membranes due to the presence of an electric field; as a consequence, the permeability of the membrane is enhanced and material diffusion throughout the membrane is achieved (An and King, 2007; Lima, 1999b). Mosqueda-Melgar et al. (2008) have confirmed the lethal effect of pulse electric fields (PEF) over potentially pathogenic microorganisms in food products, and have observed the inactivation mechanism under the electroporation theory proposed by Coster and Zimmermann (1975). The formation of pores in the cellular membrane may originate cellular lysis with the subsequent leakage of intracellular compounds due to the induced electric field (Sale and Hamilton, 1967). However, this phenomenon has been demonstrated to be reversible or irreversible, depending on the electric field intensity, the duration of the pulses, and the total number of applied pulses (Benz and Zimmermann, 1980). It is assumed that the electric breakdown or electroporation mechanism is dominant for the effects of Ohmic heating (An and King, 2007; Kulshrestha and Sastry, 2003; Sensoy and Sastry, 2004). The principal reason for this additional effect of Ohmic heating may be linked to its low frequency (usually between 50 and 60 Hz). At these low frequencies the porous cell walls allow the cell membrane of living microorganisms to build up charges and form pores (Cho et al., 1996; USA-FDA, 2000).

Yoon et al. (2002) observed that the electric field might have both direct and indirect effects on the cell wall by exuding intracellular material composed of amino acids, protein, nucleic acids, and coenzymes to the culture medium. It is stated that, below 50°C, similar amounts of exuded material were detected in the yeast supernatant, under conventional or Ohmic heating. However, at temperatures above 50°C, the concentration of exuded materials from the Ohmically heated groups were higher than those from conventionally heated groups ($p < 0.01$) and that the rate of protein exuded per unit temperature increase was found to be significantly higher ($p < 0.01$) for Ohmic heating than for conventional heating. The authors hypothesized that the higher exudation rate was not only dependent on the destruction rate of the yeast cells but also on the type of heating method. The influence of the electrical field during Ohmic heating might have increased the

rate of electroporation, thereby leading to excess exudation and cell death. Ohmic heating was also found (Yoon et al., 2002), to translocate intracellular protein materials out of the cell wall, and the amount of exuded protein increased significantly as the electric field increased from 10 to 20 V/cm. Compared to conventional heating, more amounts of protein and nucleic acids were exuded when the cells were treated with Ohmic heating. Spectroscopic analysis showed that the absorbance at 260 nm (detecting the presence of the nucleic acids) was twofold higher ($p < 0.01$) and that the total protein content was threefold higher ($p < 0.01$) with Ohmic heating at 20 V/cm when compared with Ohmic heating at 15 V/cm (Yoon et al., 2002). These authors have also observed that most of the exuded proteins came from the cell membrane and a small part from ribosome's, indicating that Ohmic heating resulted in alterations of the cell membrane by leakage of its proteins and that this effect was stronger than the one observed for conventional heating.

Imai et al. (1995) observed the occurrence of irreversible electroporation effects on *Rhaphanus sativus* L. when submitted to Ohmic heating at 45 V/cm and 50 Hz for 30 s. It was verified by H-NMR that when the radish was treated under the indicated conditions, the water present in the material had an increased mobility when compared to untreated samples. These results suggested that the rapid heating under low frequencies caused membrane electroporation in the radish tissue, resulting in the reduction of its impedance.

When applied at sub-lethal temperatures, the electroporation effect caused by Ohmic heating has also demonstrated its potential to benefit fermentative processes. Ohmic heating was applied during the fermentation of *Lactobacillus acidophilus* by Cho et al. (1996). It was observed that the presence of the electric field might have induced a faster and more efficient nutrient transport to the interior of the cells, thus reducing the lag phase of the process. Only minor changes of the pH of the medium were observed between the two processes, and both the glucose consumption and lactic acid release were not influenced by the heating method. These results indicate that Ohmic heating may show potential to shorten the initial phases of fermentative processes, thus reducing the total process time to obtain, for example, fermented dairy (Cho et al., 1996; Vicente et al., 2006). During the later stages of fermentative processes, however, Ohmic heating has demonstrated to cause decreases of productivity. Such decreases may be related with the electroporation effect, which possibly allows the transport of metabolites to the interior of the cell, consequently inhibiting the fermentative process (Cho et al., 1996; USA-FDA, 2000).

7.3.2 NONTHERMAL EFFECTS ON ENZYMES

The nonthermal effects of electric fields in enzyme inactivation may be linked with conformational disturbances of the protein structure. Enzyme denaturation can result from conformational changes and disruptions of the tertiary protein structure due to rearrangement and/or destruction of non-covalent bonds such as hydrogen bonds, hydrophobic interactions and ionic bonds. The presence of moderate electric fields may affect ionic movement in the medium and influence biochemical reactions by changing molecular spacing and increasing inter-chain reactions. Castro et al. (2004) have hypothesized that moderate electric fields may interact with the metal prosthetic group present in some enzymes (such as LOX and PPO) enhancing inactivation during heating, for example. However, this hypothesis needs to be verified (Vicente and Castro, 2007).

7.3.3 NONTHERMAL EFFECTS ON PROCESSING ALTERNATIVES

The electroporation and the consequent increase in the membrane permeability presumably induced by Ohmic heating show potential for the use of this technology, for example, to introduce molecules which, once in the cellular cytoplasm, may present antimicrobial activity. One possible molecule is the bacteriocin nisin. Nisin is an effective antimicrobial agent against Gram-positive bacteria, including strains of *Lactococcus*, *Streptococcus*, *Staphylococcus*, *Micrococcus*, *Pediococcus*, *Lactobacillus*, *Listeria* and *Mycobacterium* (Sahl et al., 1995). Gram-positive spores, such as those

from some *Bacillus* and *Clostridium* spp, are particularly susceptible to nisin, presenting higher susceptibility than the respective vegetative cells (Delves-Broughton, 1996). Nisin's effect over vegetative cells is exerted in the cytoplasmatic membrane. It acts in the formation of membrane pores causing consequent ionic misbalance and ATP hydrolysis and thus cellular death. Another mechanism of nisin action is the interference on cellular wall biosynthesis, derived from its binding affinity to lipid II, a peptidoglycan predecessor. This phenomenon is again responsible for membrane pores formation (Bauer and Dicks, 2005). It was verified by Penna et al. (2006) that, in the presence of chelating agents, such as EDTA, the activity of nisin is enhanced against *E. coli* DH5- α , a Gram-negative bacterium, expressing the recombinant GFP protein. The nisin microbial inactivation mechanism may be of particular interest to the Ohmic heating technology as, due to its action mechanism, it may present synergistic effect in the inactivation process.

7.4 FUTURE CHALLENGES AND CONCLUSIONS

Several works provide evidence that Ohmic heating presents great potential to reduce the time required for inactivation of microorganisms and some enzymes, therefore reducing the negative thermal effects of heat and opening a new perspective for shorter, less aggressive aseptic processing. In terms of process development, Ohmic heating presents challenging opportunities in food processing/preservation, as an alternative to conventional processes and the full characterization, modeling and control of all phenomena associated with application of Ohmic heating in food processing may lead to an effective control of the temperature profile of food materials (Vicente et al., 2006). However, research is still required to understand the effect that moderate electrical fields may have on the nutritive, organoleptic, and functional properties of foods. Fundamental research must be conducted regarding possible electric effects on the bio-molecules, thus, contributing to improve and optimize food processing. For example, the influence of electricity on protein structures (e.g., enzymes) must be investigated since it may lead to important conclusions that can be used not only in the food industry but also in the medical or pharmaceutical industries. A deeper understanding of current applications must be obtained and further research efforts is essential to contribute to the validation of Ohmic heating in novel applications.

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8 Effect of Ohmic Heating on Fish Proteins and Other Biopolymers

Jae W. Park and Zachary H. Reed

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8.1 INTRODUCTION

Under Ohmic heating, heat is developed when alternating current passes through electrically conducting food materials (de Alwis and Fryer, 1990). Heat is generated within the food due to its electrical resistance, resulting in a relatively rapid heating rate, depending on the chemical composition. The rate of temperature increase during the Ohmic process ranges from 1°C to 5°C/s (de Alwis and Fryer, 1992), whereas; the surface of a can in conventional sterilization is about 0.2°C/s (Datta and Hu, 1992). In general, the Ohmic process is known to reduce processing time, resulting in superior product quality compared with those processed by conventional means. However, practical application in such processes has been limited due to the problems associated with process and equipment design (Sastry and Palaniappan, 1992).

Ohmic heating has been applied to refined fish myofibrillar proteins (hereafter surimi) for the last 20 years. This fast cooking method has been utilized to evaluate the gel-forming ability of various forms of surimi and surimi seafood by Shiba and his group (Shiba et al., 1993; Shiba, 1992a, 1993). Park and his group (Yongsawatdigul et al., 1995a,b; Pongviratchai and Park, 2007a,b) studied the effect of Ohmic heating on the various forms of fish proteins to indirectly measure the proteolytic degradation of myofibrillar proteins (Yongsawatdigul and Park, 1996; Park et al., 1998) and to determine electrical properties of surimi and surimi/starch (Yongsawatdigul et al., 1995b; Pongvirthai and Park, 2007b).

This chapter will review various features of Ohmic heating in surimi and surimi seafood as affected by processing and quality parameters.

8.2 GELATION OF FISH PROTEINS BY OHMIC HEATING

8.2.1 GELATION PROPERTIES OF SURIMI UNDER OHMIC HEATING

Gelation of fish proteins is the most important step in forming the desired texture of surimi-based products. Myofibrillar proteins, especially when salted and unfolded through comminution, have highly reactive surfaces. This is why they form strong gels upon heating. Exposed reactive surfaces of the neighboring protein molecules interact with each other to form bonds. When enough bonds are simultaneously formed, a three-dimensional network can be established resulting in a gel (Lanier et al., 2005).

Whether surimi paste is heated conventionally (steam or water bath) or Ohmically, the gel-forming process, in general, is the same. However, the gelation properties can be significantly different depending on the applied heating rate. Unlike in conventional heating, Ohmic heating can develop linear heating patterns because heat is conducted uniformly by electrical resistance. It can serve as a unique tool for uniform cooking at all heating rates. Yongsawatdigul and Park (1996) demonstrated that surimi paste could be linearly heated at either a rapid or slow rate. The effect of various linear heating rates on surimi gelation was first reported by Yongsawatdigul and Park (1996). Since water bath heating provides nonlinear temperature profiles (Figure 8.1), the influence of such heating rates on gelation cannot be validated. Linear heating rates may be achieved using a programmable water bath only when slow heating rates such as 12–85°C/h are applied (Arntfield and Murray, 1992; Camou et al., 1989; Foegeding, 1987). There was an effort to develop rapid heating rates (8–15°C/min) using multiple water baths, computer simulation, and time/temperature superposition theory (Yoon and Park, 2001). However, using Ohmic heating, Yongsawatdigul and Park (1996) demonstrated a wide range of linear heating rates (1–30°C/min). It is also practically achievable to have linear heating rates between 30°C/min and 90°C/min using an Ohmic gel cooker (Park and Yongsawatdigul, 1999). Pacific whiting surimi, which is loaded with a high level of proteolytic enzymes, demonstrated better gelation properties as the heating rate increased (Figure 8.2a). In contrast, Alaska pollock surimi, which contains a minimum level of proteolytic enzymes, showed better gelation properties as the heating rate decreased (Figure 8.2b).

In other words, fast cooking is better for Pacific whiting surimi, while slow cooking is better for Alaska pollock surimi. For Pacific whiting surimi, fast cooking minimizes proteolytic degradation by maintaining a minimum amount of time spent in the activation zone of the naturally occurring proteolytic enzymes. For Alaska pollock surimi, and particularly with high grade, slow cooking provides sufficient time for the activation of transglutaminase. Subsequently, this results in the formation of covalent bonds between lysine and glutamic acid, as indicated by higher texture values at the slowest heating rate (1°C/min) (Figure 8.2b).

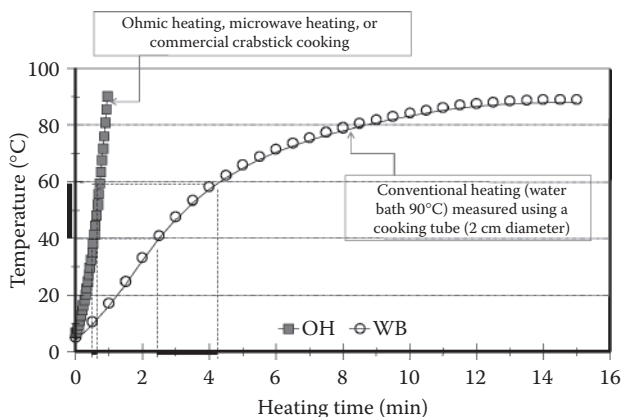


FIGURE 8.1 Heating patterns of Ohmic heating and water bath heating.

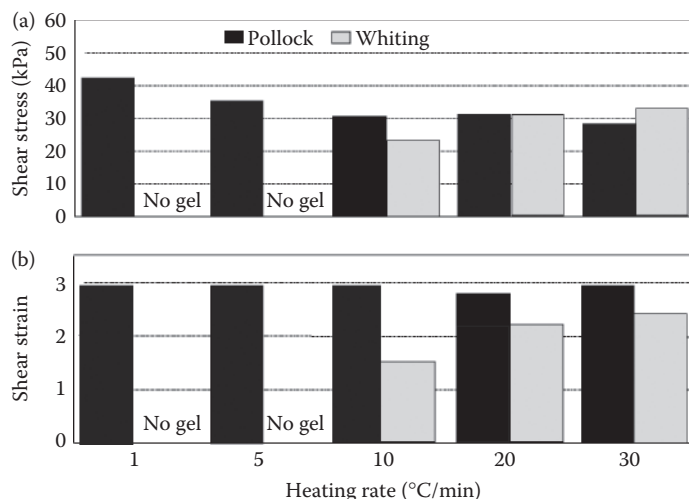


FIGURE 8.2 Textural properties of surimi gels made from Pacific whiting and Alaska Pollock as affected heating rate. (Adapted from Yongsawatdigul, J. and Park, J.W. 1996. *J Food Sci* 61(1):149–153.)

8.2.2 INDIRECT MEASUREMENT OF PROTEOLYTIC DEGRADATION

In Pacific whiting, there is a significant amount of endogenous proteases identified as cathepsin B, H, and L (Seymour et al., 1994). During the refining process of myofibrillar proteins, B and H are easily washed away, but L remains. The purified cathepsin L enzyme exhibits maximal activity at 55°C. Since the endogenous protease is heat-stable, the slow heating rate associated with conventional water bath heating methods allows the protease to hydrolyze myosin heavy chain (MHC) before it is thermally inactivated. When surimi packed in a stainless-steel tube (i.d. = 2.0 cm) is heated in a 90°C water bath, temperature at the geometric center gradually increases and remains in the activation range of the enzyme (40–60°C) for almost 2 min (Figure 8.1). This could be ample time for a hydrolytic reaction of myofibrillar proteins, especially MHC. Yongsawatdigul et al. (1995) hypothesized that once the MHC was degraded by the enzymes to a specific level, the gel network could not be properly formed regardless of the degree of degradation. As shown in Figure 8.2a, using two slow heating patterns (1 or 5°C/min), gels were too soft to measure their textural values, indicating almost all of Pacific whiting MHC was degraded. Using the Ohmic cooker and controlling the linear heating rates, the presence of proteolytic enzymes and their activity can be indirectly measured.

Yongsawatdigul and Park (1997a, b) demonstrated the degradation kinetics of texture and MHC during Ohmic heating. Degradation was best described with an apparent reaction order of 1.4. Changes of degradation rate increased with temperature and reached a maximum at 57°C. Then, the rate of MHC degradation decreased with higher temperature and reached a minimum at 75°C. E_a values of activation and inactivation zones were 142.3 and 83.1 kJ/mol, respectively.

In comparing the data generated using slow heating (conventional water bath) and fast heating (Ohmic cooker), the difference in gel texture value is the result of protein degradation by proteolytic enzymes.

8.2.3 THE DISCREPANCY BETWEEN CONVENTIONAL WATER BATH HEATING VERSUS FAST OHMIC HEATING

Gel texture is the most valuable parameter in determining the quality of surimi. The higher the gel texture quality, as typically defined by gel hardness and gel cohesiveness, the higher the surimi's

price. For surimi gel quality measurement, the most common industry practice is that surimi paste is cooked in a casing (3.0 cm diameter) in a 90°C water bath for 30–40 min. However, when crabsticks, the most common surimi seafood, are cooked in production scale, it is cooked in a continuous thin sheet (1.2–2.0 mm thick). This process results in heating to 90°C within 20–40 s, depending on the operation scheme with a combination of gas and/or steam heat (Figure 8.1). The gel texture of surimi, depending on species and surimi grade, is also significantly affected by the heating rate (Yongsawatdigul and Park, 1996). There is an obvious discrepancy in gel textural values obtained from the two different heating patterns. Applying the gel texture data obtained from slow conventional water bath heating to the production of fast cooking crabsticks does not assure reliable quality and production optimization.

To overcome the gel-softening effect of proteolytic enzyme-laden surimi under slow cooking, food-grade enzyme inhibitors (i.e., plasma protein, egg white, or whey protein concentrate) have been used. However, due to the dual function of protein additives as a proteolytic enzyme inhibitor and gelling agent, the use of an enzyme inhibitor does not assess the quality of proteolytic enzyme-laden surimi accurately. Therefore, the most accurate gel assessment for proteolytic enzyme-laden surimi is to cook fast by using Ohmic heating.

As shown in Figure 8.1, when surimi paste, stuffed in a 2 cm diameter casing, is cooked in a conventional water bath (90°C), proteolytic enzymes are exposed to their active temperature zone (40–60°C) for about 2 min. This is long enough for proteolytic enzymes to hydrolyze myofibrillar proteins, resulting in extremely soft or no gels. However, when the same paste is cooked Ohmically at 220 V, they were exposed to 40–60°C for less than 15 s (Figure 8.1). This is short enough for proteolytic enzymes not to degrade MHC. With them being inactivated beyond 75–80°C depending on species, the myofibrillar proteins will complete gelation sufficiently (Park, 2005).

Those who manufacture surimi and those who manufacture crabsticks must understand the nature of this discrepancy. For accurate quality assessment and good quality assurance, surimi gel preparation must, therefore, be done using a fast heating mode (i.e., Ohmic heating) to mimic the actual cooking process for crabsticks and other fast cooked surimi seafood (i.e., fried surimi seafood).

8.2.4 THE EFFECT OF VOLTAGE OR VOLTAGE GRADIENT

A high breaking force and distance values are desirable and are an indication of high-quality surimi gel. A final internal temperature of 90°C has been established as an industry guideline (FAO/WHO, 2000) for surimi gel cooked in a water bath. An investigation of Pacific whiting surimi was performed to determine gel fracture force and distance as affected by final internal cooking temperatures of 80°C and 90°C using Ohmic cooking. Force values (186.7 g at 80°C, 191.7 g at 90°C) and distance values (11.9 mm at 80°C, 11.5 mm at 90°C) showed no significant difference between treatments. This is probably due to the fact that all fish proteins are completely cooked when the internal temperature exceeds 75°C (Thawornchinsombut and Park, 2007).

We attempted various trials to see the effect of different voltages and voltage gradients at 5 kHz. With a fixed sample length (15 cm), the use of 200 and 250 V generated a voltage gradient of 13.3 and 16.7 V/cm, respectively. Table 8.1 shows that all Ohmically cooked Pacific whiting surimi (PW) at 200 and 250 V showed an increase in gel strength, compared to that of the conventional water bath (WB) cooked surimi. This indicates the presence of heat-induced proteolytic enzymes in Pacific whiting surimi. Gel fracture and distance values indicate a significant difference between PW gels heated at 200 and 250 V. The PW gels cooked at 200 V had average values of 192.3 g and 10.96 mm. 250 V was therefore chosen for ingredient testing because of the higher resulting force (205.7 g) and distance (12.13 mm) values produced, respectively. Results show that heating surimi gel to 80°C using 250 V and no holding time produced the highest gel fracture and distance values, 231.4 g and 12.9 mm, respectively.

AA grade Alaska pollock surimi (AP) is considered medium grade surimi, with very little or no enzymatic degradation, which is supported by the average gel force and distance values (215.7 g and

TABLE 8.1

Effects of Holding Time on Gel Fracture Force and Distance Value for Pacific Whiting (PW) and Three Grades of Alaska Pollock (AP) AA, KA, and RA, Respectively

	Force (g)							
	200 V				250 V			
	WB	0	45	90	WB	0	45	90
PW	27.0 ^a	187.7 ^b	196.1 ^{b,c}	193.1 ^{b,c}	27.0 ^a	231.4 ^c	184.8 ^b	201.0 ^{b,c}
AP (AA)	214.0 ^a	197.5 ^a	194.3 ^a	211.4 ^a	217.4 ^a	214.8 ^a	221.1 ^a	222.9 ^a
AP (KA)	238.1 ^{a,b}	207.8 ^a	223.3 ^a	246.9 ^{a,b,c}	295.6 ^d	275.7 ^{b,c,d}	285.0 ^{c,d}	284.8 ^{c,d}
AP (RA)	106.1 ^a	151.2 ^{b,c}	163.3 ^{c,d}	192.9 ^{c,d,e}	120.8 ^{a,b}	193.9 ^{d,e}	189.7 ^{c,d,e}	205.9 ^e

	Distance (mm)							
	200 V				250 V			
	WB	0	45	90	WB	0	45	90
PW	6.5 ^a	10.9 ^b	11.2 ^b	10.8 ^b	6.5 ^a	12.9 ^c	11.5 ^{b,c}	12.0 ^{b,c}
AP (AA)	10.3 ^a	11.6 ^{a,b,c}	11.4 ^{a,b,c}	12.5 ^{b,c}	10.6 ^{a,b}	12.0 ^{a,b,c}	12.9 ^c	12.8 ^c
AP (KA)	10.7 ^a	11.6 ^{b,c}	12.3 ^b	13.1 ^{b,c}	12.6 ^b	14.4 ^c	14.3 ^c	14.3 ^c
AP (RA)	5.6 ^a	9.7 ^b	10.2 ^{b,c}	11.3 ^{b,c}	6.5 ^a	12.0 ^c	11.3 ^{b,c}	11.4 ^{b,c}

Note: Different letters indicate a significant difference ($p < 0.05$) among samples in the same row. Water bath (WB) samples were cooked at 90°C for 30 min, while Ohmically cooked samples were cooked at either 200 or 250 V to an internal temperature of 80°C and held for 0, 45, or 90 s.

10.5 mm for WB, 210.3 g and 12.2 mm for OH). Statistical analysis showed there was no significant difference between conventional and Ohmic cooking for AA grade Alaska pollock (Table 8.1), indicating that there is little presence of proteolytic enzymes in this high grade pollock surimi. KA grade Alaska pollock surimi, however, showed that average gel force and distance values cooked at 200 and 250 V were significantly different. RA grade surimi, which is the lowest grade in Alaska pollock surimi, showed results more similar to those of PW than any of the other grades of AP surimi. When Ohmically cooked gel values were compared according to cooking voltage, gels cooked at 200 V showed significantly lower average values than those cooked at 250 V (Table 8.1). This indicates that RA grade Alaska pollock surimi possibly contained some endogenous enzymes exhibiting proteolytic activity (Reppond and Babbitt, 1993; Yoon et al., 1997).

Protein additives, such as dried egg white and whey protein concentrate, have been used as protease inhibitors in surimi production for many years. Pacific whiting surimi gels without any enzyme inhibitors cooked in water bath (WB) and cooked Ohmically (OH) at 250 V showed force values of 9.7 and 209.5 g with distance values of 0.0 and 12.1 mm, respectively (Figure 8.3). When dried egg white (DEW) was added to surimi gels, the enzyme inhibitory activity was evidenced by significantly increased force values of 131.8 and 295.1 g and distance values of 6.9 and 13.0 mm for the WB and OH cooked samples, respectively. These results are in agreement with enzyme inhibition studies done by Chang-Lee et al. (1989). An et al. (1994) and Yongsawatdigul et al. (1997) also demonstrated degradation of the MHC due to proteolytic enzyme activity in the slow cooking of conventional water bath.

Gels cooked Ohmically performed significantly ($p < 0.05$) better than those cooked conventionally in a water bath (Figure 8.3). Whey protein concentrates (WPC) had similar effects on surimi gels when added as an enzyme inhibitor. Pacific whiting surimi gels with 2% WPC cooked conventionally (CON) and Ohmically (OH), at 250 V, yielded force values of 131.8 and 295.1 g with distance values of 6.9 and 13.0 mm, respectively. The increased force and distance values are in

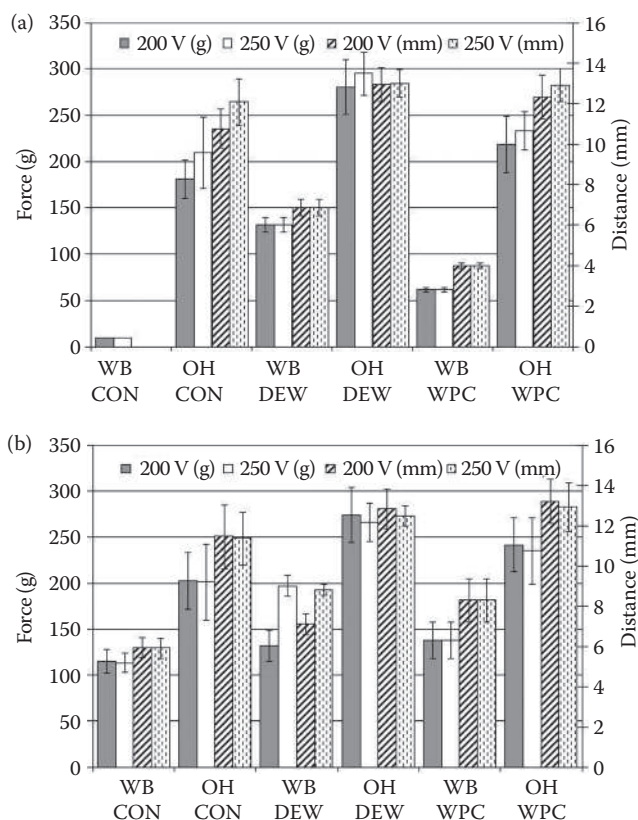


FIGURE 8.3 Textural properties of (a) Pacific whiting and (b) Alaska pollock (RA) surimi as affected by heating rate and/or protein additives.

agreement with studies done by Piyachomkwan and Penner (1995) which indicated that autolysis was virtually undetectable when surimi was supplemented with 2% WPC.

Alaska pollock surimi RA grade, which is known as recovery or low grade, showed similar results to those of Pacific whiting surimi when subjected to the same ingredient testing (Figure 8.3). For RA grade Alaska pollock with no addition of enzyme inhibitors, cooked gels had force values of 113.3 and 201.3 g with distance values of 5.9 and 11.4 mm for CON and OH (250 V), respectively. When pollock RA grade surimi was mixed with 2% DEW, force values of 197.2 and 266.4 g with distance values of 8.8 and 12.5 mm were obtained showing an increase in both force and distance values compared to gels made with no protein additives. A similar trend was noted for the 2% WPC gels with force values of 138.0 and 235.2 g and distance values of 8.3 and 12.9 mm for the WB and OH cooked gels, respectively. As can be seen in Figure 8.3, Ohmically cooked gels had significantly ($p < 0.05$) higher force and distance values than the water bath cooked counterparts regardless of the type of enzyme inhibitor used.

To measure proteolytic degradation during heating, Pacific whiting (PW) and Alaska pollock (AP) RA gels were analyzed using SDS-PAGE analysis (Figure 8.4). PW water bath samples showed degradation of MHC as compared to Ohmically cooked samples regardless of holding times. The RA grade pollock samples showed a similar trend to that of PW water bath cooked samples showing lower MHC than RA OH samples at 200 and 250 V. It is of interest to note that although there was degradation of MHC in the pollock, RA samples the degradation was not as complete as that of the PW samples.

When protein inhibitors were added to the surimi paste, proteolytic enzyme activity of the MHC was reduced (Figure 8.5). For PW, MHC degradation was greatest in samples cooked in a

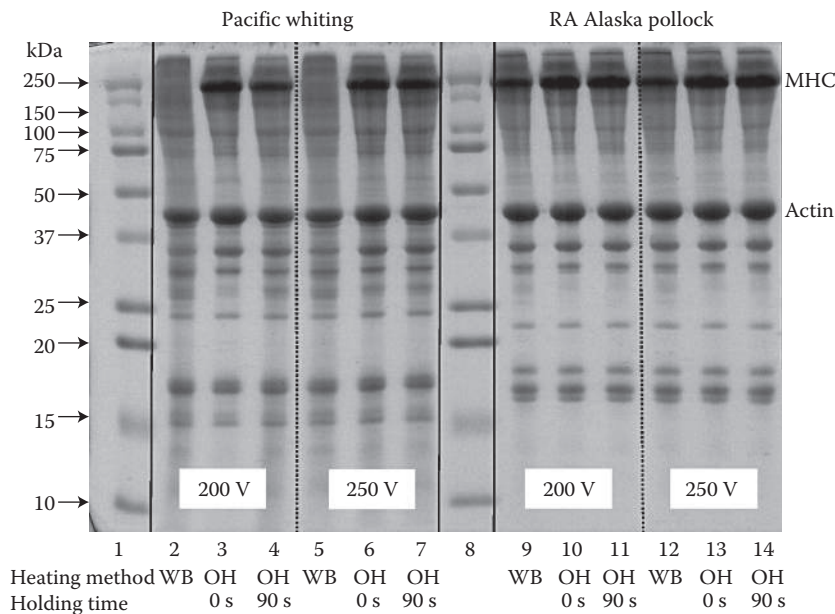


FIGURE 8.4 Degradation of MHC was significantly minimized when surimi was cooked Ohmically as shown in SDS-PAGE. WB, water bath cooking; OH, Ohmic heating; s, holding time (s) after the core temperature reached 90°C.

water bath without protein inhibitors, which is supported by Akazawa et al. (1993). It can be seen that MHC degradation of all Ohmically cooked PW samples was less than that of the WB cooked samples from the same batch. When cooked in a water bath, the Alaska pollock RA grade showed reduced degradation of MHC compared to PW, indicating the predominant role of proteolytic enzymes in PW.

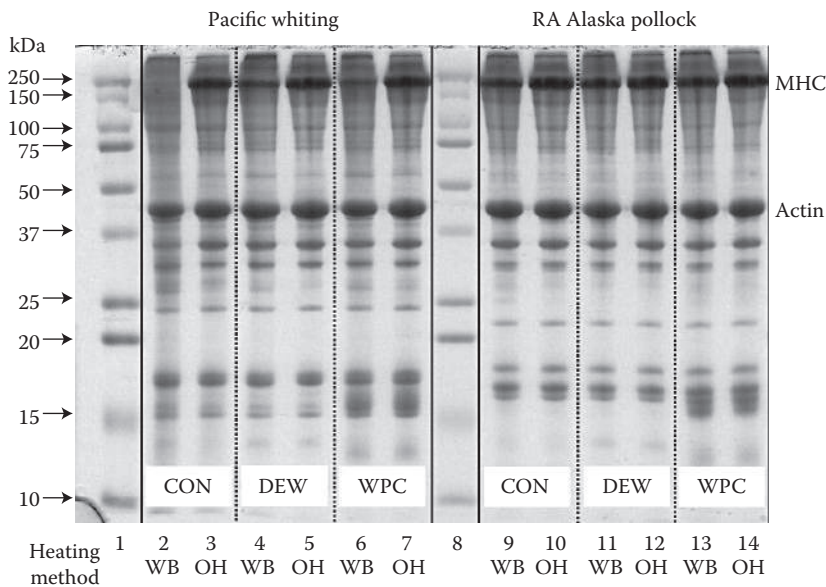


FIGURE 8.5 Degradation of MHC as affected by heating rate and/or protein additives. WB, water bath cooking; OH, Ohmic heating. DEW, dried egg white; WPC, whey protein concentrate.

8.2.5 THE EFFECT OF APPLIED FREQUENCY

An electrolytic reaction could take place at the electrode surface while conducting 60 Hz Ohmic heating tests with current density exceeding 3500 A/m² and sample salinity up to 4% (Shiba, 1992a,b; Yongsawatdigul et al., 1995a). Wu et al. (1998) reported fish protein samples tested at 55 and 500 Hz (with the current density up to 3000 A/m²) experienced corrosion with a light-brown porous coat in an irregular pattern at low salt concentration (1%) and more uniform coat at higher concentrations. Corrosion on stainless-steel electrodes at low frequency was inevitable because surimi paste contained 2–3% salt and 75–80% moisture. When the applied frequency exceeded 5 kHz, corrosion on the electrode surface and burning of the sample were no longer visible (Wu et al., 1998; Zhao et al., 2000). However, as the electrodes were used continuously for surimi paste salted at 2–3%, we noted that the color of the electrodes was no longer shiny and clean, indicating there is still accumulation of corrosion at 5 kHz. Our further study verified that 10 or 15 kHz did not show any signs of corrosion even when the electrodes were continuously used with surimi paste salted at 2–3%.

In our recent gel-testing study, Pacific whiting surimi gels were cooked to a final internal temperature of 90 or 95°C using 5 or 15 kHz and then held for 0 or 2 min. Gels made with 90°C cooking and holding for 0 or 2 min performed much better than those with 95°C cooking for gel strength and cohesiveness (Figure 8.6).

As for the effect of applied frequency, 15 kHz performed better for gel strength. However, there was no significant difference between the two frequencies on gel cohesiveness as denoted by distance values. Better gel strength of Pacific whiting surimi cooked with 15 kHz was thought to be due to the slightly faster heating rate. At 15 kHz, we obtained a heating rate of 2.6°C/s, and a rate of 2.4°C/s at 5 kHz. As explained above, proteolytic enzyme-laden Pacific whiting surimi performed better as the residual time at the enzyme's active zone (40–60°C) reduced before thermally being inactivated as the temperature exceeded 70°C (Yongsawatdigul and Park, 1996).

8.3 ELECTRICAL CONDUCTIVITY

To optimally design the Ohmic process, electrical conductivity of food materials during Ohmic heating must be elucidated. Conductivity is a critical parameter influencing the rate of heat generation

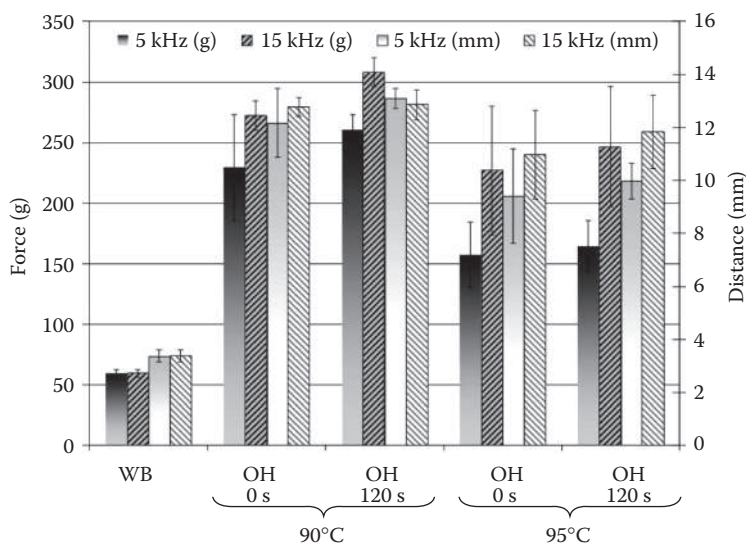


FIGURE 8.6 Textural properties of Pacific whiting surimi gels cooked Ohmically as affected by final cooking temperature, applied frequency, and holding time. WB, water bath cooking; OH, Ohmic heating.

(Palaniappan and Sastry, 1991a; de Alwis and Fryer, 1992). Electrical conductivities were measured on various products using low alternating current (50 or 60 Hz) (Halden et al., 1990; Palaniappan and Sastry, 1991a, b; Yongsawatdigul et al., 1995b), fish mince using low-to-high alternating current of 55 Hz–200 kHz (Wu et al., 1998), and surimi–starch paste or surimi–protein additive paste using low- and mid-alternating currents of 55 Hz–20 kHz (Pongviratchai and Park, 2007a). Wu et al. (1998) reported that the sample impedance decreased with applied frequency for Pacific whiting surimi paste and stabilized mince. DC electrical conductivity increased with temperature and salt concentrations.

Yongsawatdigul et al. (1995b) reported that electrical conductivity was highly dependent on temperature and added salt content and slightly dependent on the moisture content of surimi paste. Increased electrical current due to ions (Na^+ and Cl^-) was responsible for increased electrical conductivity. Increased conductivity at high moisture content was due to increased ionic mobility through better ion salvation. Electrical conductivity was linearly correlated with temperature. The voltage gradient did not affect conductivity of fish proteins while being heated. However, variations of conductivities with a voltage gradient were observed in surimi containing 3–4% salt, indicating the possible electrochemical reactions at electrode surfaces at high salt concentrations.

Pongviratchai and Park (2007a) studied electrical conductivities of Alaska pollock surimi mixed with native and pregelated potato starch (0%, 3%, and 9%) prepared at 75% and 81% moisture concentrations using a multifrequency Ohmic heating system. Electrical conductivity increased when moisture content, applied frequency, and applied voltage increased, but decreased when starch concentration increased. Electrical conductivity was linearly correlated with temperature. Electrical conductivity patterns (magnitude) changed when temperatures increased, which was clearly seen after 55°C in the native potato starch system, especially at high concentration. This indicated that starch gelatinization which occurred during heating affected electrical conductivity (Pongviratchai and Park, 2007a).

8.4 STARCH AND NONMUSCLE PROTEIN ADDITIVES

Surimi seafood is commonly manufactured using surimi and other ingredients, such as starches, nonmuscle protein additives, oil, color, and flavor (Park et al., 1997). The most popular surimi seafood in the United States and Europe are crabsticks. In commercial crabstick processing, paste extruded as a continuous thin sheet reaches 90°C under steam or gas heating in less than 1 min. This rapid cooking process completes fish protein gelation, but it does not provide enough time for starch gelatinization (Park, 2005).

Starch is the second major ingredient used in surimi seafood because it maintains good texture at reduced surimi content and also improves shelf life (Park, 2005; Kim and Lee, 1987; Yang and Park, 1998). Native starch granules are insoluble or poorly soluble in cold water, but when they are heated to a specific temperature, called the gelatinization temperature, they become swollen and dramatically increase the viscosity of the suspension (Waniska and Gomez, 1992). The type and concentration of starch can affect gel properties due to its swelling and water uptake during heating (Lee et al., 1992; Park, 2005).

In the surimi–starch system, the high strength of Ohmic gels cooked slowly might be the result of not only the setting effect, but also the retrogradation of leaking amylase (Pongviratchai and Park, 2007b). Table 8.2 showed that surimi with a low concentration of starch cooked under the Ohmic method had the best results. This higher gel strength was thought to be due to the combined effect of the starch and heating method.

Nonmuscle protein additives are generally used to improve textural properties and nutritional value. The effects of protein addition in surimi gels was previously observed with regard to textural properties and color functionality (Park, 1994). Gel network structure and gel matrix development (Lanier, 1991) were studied as a function of protein additives. However, the majority of these studies were conducted using gels prepared in hot water, providing little information for starch and protein additives in surimi gel cooked under Ohmic heating, which more closely mimics the commercial cooking time and heating rate of surimi crabsticks (Pongviratchai and Park, 2007b).

TABLE 8.2
Textural Properties of Surimi-Starch Gels Cooked under Ohmic Heating

Parameter	Cooking Method	Treatments				
		Control	3 W	9 W	3P	9P
Shear stress (kPa)	200 V	42.92 ^{BC1}	47.88 ^{C12}	35.31 ^{A1}	48.48 ^{C12}	39.71 ^{AB2}
	55 V	50.81 ^{B2}	52.57 ^{B2}	38.78 ^{A1}	54.61 ^{B2}	38.09 ^{A2}
	WB	38.32 ^{B1}	44.52 ^{B1}	38.38 ^{B1}	41.97 ^{B1}	30.35 ^{A1}
Shear strain	200 V	2.94 ^{A1}	3.15 ^{B2}	3.21 ^{B1}	3.08 ^{AB2}	2.99 ^{AB2}
	55 V	2.86 ^{AB1}	3.00 ^{BC12}	3.00 ^{BC1}	3.11 ^{C2}	2.64 ^{A1}
	WB	2.79 ^{A1}	2.89 ^{A1}	3.15 ^{B1}	2.86 ^{A1}	2.78 ^{A12}

Source: Pongviratchai, P. and Park, J.W. Physical properties of fish proteins cooked with starches or protein additives under Ohmic heating. *J Food Quality* 2007b. 30:783–796. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

Note: W, wheat starch; P, potato starch; WB, water bath cooking; 200 and 55 V, Ohmic cooking at 200 and 55 V, respectively.

^{A–C} The significant differences among treatments within the same cooking method (within each row).

^{1–3} The significant differences among cooking methods within the same treatment (within each column of each parameter).

Pongviratchai and Park (2007b) studied the textural gel properties of surimi seafood as affected by type and concentration of additives, as well as by cooking methods, including Ohmic heating. Shear stress, representing gel strength, showed that both potato and wheat starch could suitably replace fish myofibrillar proteins at low concentrations (3%) (Table 8.2). However, when starch concentration increased to 9%, shear stress decreased significantly, indicating excessive amounts of starch could inhibit the gel-forming ability of fish proteins.

Temperature and time are two of the most important factors that influence both gelatinization of starch and gelation of fish proteins in a surimi–starch system (Yang and Park, 1998). Yang and Park (1998) as well as Wu et al. (1985) found myofibrillar proteins were thermally denatured before starch was completely gelatinized. In addition, gelatinization of starch in a surimi–starch system shifts to a higher temperature compared to a starch–water system due to the presence of myofibrillar protein and other food additives (salt, sugar, sorbitol, etc.) (Park, 2005).

Shear strain, a good indicator of protein–protein interaction, is generally not affected by processing. However, the result (Table 8.3) showed that starch could somehow improve gel cohesiveness whether cooked in water bath or Ohmically. There was also a significant effect of the heating rate on gel strain. Ohmic gels gave higher shear strain than water bath gels, indicating the surimi used in this study might have had a certain degree of protease enzymes.

Ohmic gels demonstrated higher gel strength than conventionally cooked gels, except with beef plasma protein (BPP) treatments (Table 8.3). BPP appeared to work as an effective proteolytic enzyme inhibitor. Ohmic heating generates uniform heat internally throughout the product, leading to uniform unfolding of myofibrillar proteins. Fast Ohmic heating seemed to show improved shear strain values for surimi–protein gels.

8.5 COMMERCIAL APPLICATION

Two Japanese manufacturers have introduced a commercial scale Ohmic cooker for producing crabsticks, the most popular form of surimi seafood in the Western world (Park, 2005). For the manufacture of filament-style crabsticks, a continuous thin sheet of surimi seafood paste is extruded onto a wet fabric conveyor belt that is located above the Ohmic electrodes (Figure 8.7). Many stainless-steel electrodes, consisting of anodes and cathodes placed one after another at a 10–20 mm distance,

TABLE 8.3
Textural Properties of Surimi-Protein Additive Gels Cooked under Ohmic Heating

Parameter	Cooking Method	Treatments			
		Control	BPP	EW	WPC
Shear stress (kPa)	200 V	39.18 ^{A2}	39.70 ^{A12}	40.22 ^{A2}	45.36 ^{A2}
	55 V	47.98 ^{B3}	45.55 ^{B2}	35.32 ^{A2}	45.75 ^{B2}
	WB	33.76 ^{B1}	39.27 ^{C1}	28.76 ^{A1}	38.18 ^{BC1}
Shear strain	200 V	2.96 ^{A2}	2.89 ^{A1}	3.10 ^{A3}	3.14 ^{A2}
	55 V	2.88 ^{A12}	2.75 ^{A1}	2.72 ^{A2}	3.08 ^{A2}
	WB	2.68 ^{B1}	2.79 ^{B1}	2.28 ^{A1}	2.78 ^{B1}

Source: Pongviratchai, P. and Park, J.W. Physical properties of fish proteins cooked with starches or protein additives under Ohmic heating. *J Food Quality* 2007b. 30:792. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

Note: W, wheat starch; P, potato starch; WB, water bath cooking; 200 and 55 V, Ohmic cooking at 200 and 55 V, respectively.

^{A-C} Significant differences among treatments within the same cooking method (within each row).

¹⁻³ Significant differences among cooking methods within the same treatment (within each column of each parameter).

revolve to move the belt as a roller. The electric current is sent from one cathode to the next anode through the wet fabric belt and the heat is induced between the electrodes (Park, 2005). The thin surimi paste sheet, which conducts heat very effectively, with increased moisture and salt content (Yongsawatdigul et al., 1995b), is cooked to form an elastic gel sheet. Since the heat is conducted within the surimi paste during Ohmic cooking, the removal of air pockets in the sheet is very critical for uniform heat generation. Therefore, the use of a vacuum silent cutter is highly recommended during the comminution of surimi (Park, 2005).

Unlike crabstick cooked in a thin sheet, Japanese fish cake (kamaboko) is steam cooked in a half-moon shape on a wooden board. There is an obvious difference in heat penetration between cooking methods for the two products. The latter slow heating method is not able to utilize low- to medium-grade surimi that typically contains a decent level of proteolytic enzymes. However, by combining

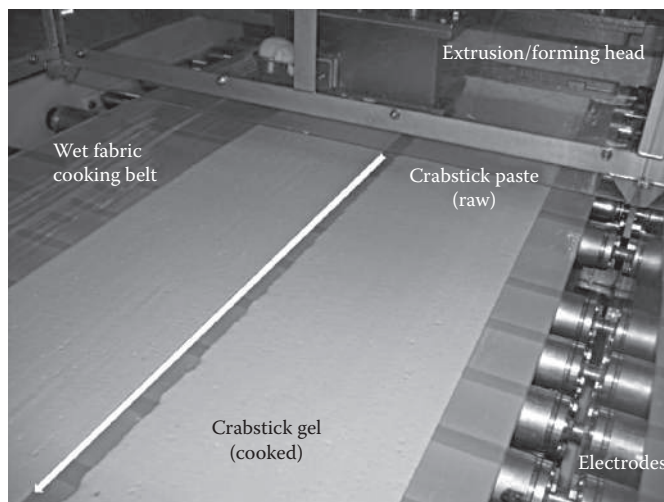


FIGURE 8.7 Ohmic cooking machine for crabstick. (Courtesy of BIBUN, Tokyo, Japan.)

conventional steam heating with Ohmic heating, which significantly improved heat penetration, low- to medium-grade surimi was subsequently utilized for kamaboko production.

In addition to commercial applications of Ohmic heating for crabstick and kamaboko manufacture, there is a recent effort to apply Ohmic heating for the accurate assessment of surimi gel to replace conventional water bath cooking. As described above, there is a significant discrepancy between fast Ohmic and slow water bath heating. The most accurate surimi quality can be assessed when surimi paste is cooked rapidly in an Ohmic cooker. Ohmic gel cooking equipment is now sold under RAPSA® (rapid, accurate, portable surimi analyzer) by Kami Steel (Seattle, WA, USA).

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9 Electrochemical Reactions during Ohmic Heating and Moderate Electric Field Processing

Chaminda P. Samaranayake and Sudhir K. Sastry

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9.1 INTRODUCTION

In electrochemistry, heat generation due to the passage of electric current is typically unwanted and a nuisance. Particularly in electrosynthetic applications where electrochemical reactions are of paramount importance, the heat generation is certainly one of the most serious limiting factors. This annoying phenomenon is, however, profitable in applications in which rapid and uniform heating are desired. Eigen (1954, p. 194, 199) used this phenomenon for scientific purposes referring it as the “temperature jump method.” In food processing, this phenomenon is of great advantage and is often referred to as Ohmic heating. Generally, electric fields with field strength under 100 V/cm are used for Ohmic heating. Since Ohmic heating has exactly the reverse objective of electrosynthesis, we revisit Ohmic heating here from an electrochemistry point of view.

9.2 ELECTRODE/SOLUTION INTERFACE

In Ohmic heating, the passage of electric current through the heating cell is ideally used only for heat generation; electrochemical reactions at electrode/solution interfaces are considered undesirable. To understand the electrochemical behavior of Ohmic heaters, it is necessary to identify

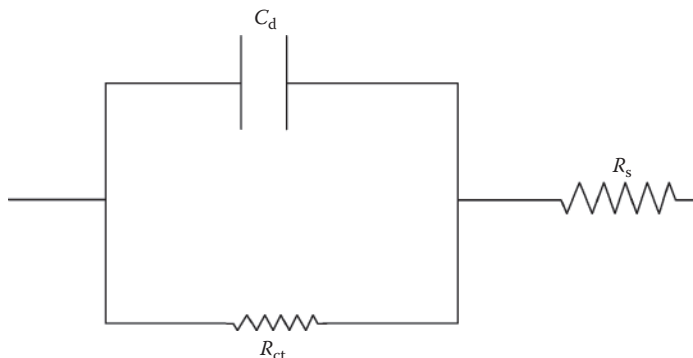


FIGURE 9.1 A, simplified electrical equivalent circuit of the electrode/solution interface during the application of AC; C_d , electrical double-layer capacitor; R_{ct} , charge-transfer resistance; R_s , electrolyte resistance.

the characteristics of the electrode/solution interface. As described in interfacial electrochemistry, the electrode/solution interface is analogous to a parallel combination of a resistor and a capacitor (Rubinstein, 1995). A simplified electrical equivalent circuit of the interface during the application of alternating current (AC) is shown in Figure 9.1. In reality, the so-called electrical double-layer capacitor (C_d) can hold only a limited number of charges. Once it is fully charged or “saturated” it becomes a “leaky” capacitor and charge transfer occurs between the plates of the capacitor, generating faradaic current, and consequently, initiating electrochemical (i.e., faradaic-type) reactions.

However, most electrode/solution interfaces also exhibit a potential range (1–2 V wide at most) where no faradaic reactions can take place. If the potential difference across the double layer is maintained within its faradaic reaction-free potential window, electrons from the electrode cannot be transferred to the electrolyte and nor can ions from the electrolyte react at the electrode. The only phenomenon occurring at the electrode is a periodic change in the charge density on both sides of the interface. Under such circumstances the current flowing through the interface becomes purely capacitive. Thus, one wants to increase the capacitive current for Ohmic heating to avoid significant electrochemical reactions.

9.3 ELECTROCHEMICAL REACTIONS

In AC circuits, both current and voltage oscillate as a wave at a certain frequency. When AC is applied to an electrolytic cell, the double-layer capacitors of the electrode/solution interfaces, charge and discharge periodically. If the frequency of the AC wave is low, the capacitors can be fully charged during the rising part of the wave turning on electrochemical reactions. Those reactions involve simultaneous cathodic (i.e., reduction) and anodic (i.e., oxidation) half-reactions; the overall reactions produce periodic concentration changes of redox species at the electrode surfaces. The extent of those chemical changes primarily depends upon the frequency of the applied AC signal and the chemistry of the electrolytic cell.

9.3.1 HISTORY OF AC INDUCED ELECTROCHEMICAL REACTIONS

Electrochemical reactions induced by AC were first reported in the early nineteenth century and were a common difficulty encountered in measuring the conductivity of electrolytes. Shaw (1950) reported that when an alternating current is applied to an electrolytic cell, the cell shows both dissipative and reactive characteristics. Bentley et al. (1957) observed corrosion of stainless-steel, platinum, and gold electrodes when low-frequency (50 Hz) alternating currents were passed through

concentrated acids; this corrosive effect was not evident at frequencies greater than a few kHz. They further encountered distorted voltage waveforms across the test cells at 50 Hz and attempted to correlate this waveform distortion with corrosion. Most of the early investigations of AC-induced electrochemical reactions have been briefly reviewed by Kulman (1961). He implied that AC-induced electrolysis is closely associated with the corrosion of electrodes. Venkatesh et al. (1979) have also reviewed some fundamentals of AC-induced electrochemical reactions. Their discussion indicates that when a sinusoidal alternating electric field is applied to an electrolytic cell, a direct current (DC) or a “faradaic rectification current” is generated at each of the electrode surfaces; this DC component is related to the amplitude of the applied voltage signal. Venkatachalam et al. (1981) gave a discussion and reviewed AC-induced anodic and cathodic reactions and the effect of frequency. Lalvani et al. (1994, 1996) and Bosch et al. (1998) carried out some theoretical studies for predicting AC-induced corrosion. They also reported that the corrosion behavior strongly depends on the amplitude of the applied voltage signal.

9.3.2 ELECTROCHEMICAL REACTIONS DURING OHMIC HEATING

Typically, Ohmic heaters are powered by low-frequency (50–60 Hz, sine wave) AC coming from the public utility supply because that minimizes the cost and power supply complexity. Under such alternating frequencies, a part of the current passing through the electrode/solution interfaces causes electrochemical reactions. Since food materials are inherently a complex mixture of several different chemical compounds, a number of electrochemical reactions can potentially occur during the Ohmic heating of food. The following are the most commonly encountered and well-known electrochemical reactions.

1. Electrode corrosion
2. (Partial) Electrolysis of the heating medium

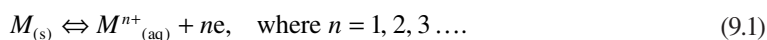
Stirling (1987) first reported the occurrence of such electrochemical reactions during Ohmic heating. He demonstrated the selection of safe maximum current density that restricts faradaic current to less than 0.1% of the total current using a platinized-titanium/saturated NaCl Ohmic heating cell. Palaniappan and Sastry (1991), Uemura et al. (1994), Assiry (1996), Reznick (1996), Wu et al. (1998), and Assiry et al. (2003, 2006) observed apparent electrolysis of the heating medium and electrode corrosion during Ohmic heating. Some of these authors reported that electrochemical effects diminish with increasing frequency. Amatore et al. (1998) gave a broad discussion of fundamental electrochemistry related to Ohmic heating. They suggested using high alternating frequencies to inhibit electrochemical reactions. Tzedakis et al. (1999) has examined the electrochemical behavior of platinum and platinized-titanium electrodes for Ohmic sterilization of some commercial food products. Their results indicate that at the frequency of 50 Hz only platinized-titanium would be capable of suppressing electrochemical behavior. The potential use of platinized-titanium electrodes for Ohmic heating of food with 60 Hz AC has been further demonstrated by Samaranayake and Sastry (2005). Samaranayake et al. (2005) have introduced a high-frequency, pulsed Ohmic heating technique, as an alternative to the conventional (50–60 Hz, sine wave) Ohmic heating. This pulsed technique is shown to be very effective in minimizing the electrochemical reactions during Ohmic heating.

9.4 POSSIBLE EFFECTS ON FOOD PROCESSING

In addition to the primary electrochemical reactions at the interfaces, the products of these electrochemical reactions may initiate a number of secondary chemical reactions during Ohmic heating. Although it is not possible to examine the effects of all the electrochemical and subsequent chemical reactions, the following effects on food processing by Ohmic heating cannot be overlooked.

9.4.1 THE EFFECTS OF ELECTRODE CORROSION

During Ohmic heating, electrode corrosion occurs via electro-dissolution induced by low-frequency AC. There have been various electrode materials used in different Ohmic heating studies and applications (Table 9.1). For metallic electrodes (M), a generalized anodic half-reaction for the electrode corrosion can be written as follows:



The metal ions (M^{n+}) migrating into the heating medium are contaminants and may be toxic beyond a certain level. However, on the other hand, the electrode corrosion might represent an opportunity to introduce essential minerals into the processed foods. Since food systems are generally rich in ligands, the migrated transition metal ions can form various coordination complexes. These metal complexes typically have characteristic colors and, therefore, may involve in alteration of the color of the processed food. It is also known that some transition metal ions have catalytic effects for certain food reactions, such as lipid oxidation. Therefore, electrode corrosion may have an impact on flavor quality of the processed food.

The corrosion of carbon (graphite) electrodes yields soluble organic compounds because of the migration of surface functional groups and oxides during Ohmic heating (Samaranayake and Sastry, 2005). Since these organic compounds contain several carbon atoms per molecule, carbon electrodes exhibit a higher corrosion rate and extensive electrode wear compared to metallic electrodes.

TABLE 9.1
Electrode Materials Used for Ohmic Heating Studies and Applications

Electrode Material	Reference
Aluminum	Mizrahi et al. (1975) Uemura et al. (1994)
Carbon (graphite)	Getchell (1935) Moses (1938) Samaranayake and Sastry (2005) Samaranayake et al. (2005)
Dimensionally stable anode (DSA)-type	Amatore et al. (1998)
Glassy carbon	Amatore et al. (1998)
Platinum	Tzedakis et al. (1999)
Platinized-titanium	Stirling (1987) Tzedakis et al. (1999) Samaranayake and Sastry (2005) Samaranayake et al. (2005)
Rhodium plated stainless steel	Palaniappan and Sastry (1991)
Stainless steel	Amatore et al. (1998) Assiry (1996) Assiry et al. (2003, 2006) Wu et al. (1998) Samaranayake and Sastry (2005) Samaranayake et al. (2005)
Titanium	Amatore et al. (1998) Samaranayake and Sastry (2005) Samaranayake et al. (2005)

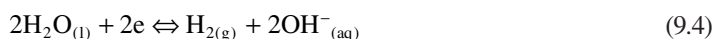
9.4.2 THE EFFECTS OF ELECTROLYSIS

Since most food formulations subjected to Ohmic heating contain more than 50% water, the low-frequency AC induces electrolysis of the water generating H_2 and O_2 gases at the electrode/solution interfaces. The corresponding anodic and cathodic half-reactions and the overall electrolysis reaction are as follows.

Anodic half-reaction:



Cathodic half-reactions:



The overall reaction:



Molecular oxygen generated by electrolysis can oxidize almost all the oxidizable food components, particularly lipids and vitamins like ascorbic acid (vitamin C). The molecular oxygen also involves electrode corrosion or formation of insulating species on the electrode surfaces partially passivating the electrodes (Tzedakis et al., 1999). Because of the high flammability and explosive nature of hydrogen, its uncontrolled liberation might pose safety concerns.

The liberation of gas bubbles at the electrode/solution interfaces does not necessarily indicate the overall electrolysis reaction (Equation 9.5). Sometimes, the anodic half-reaction for electrode corrosion (Equation 9.1) may be accompanied with one of the cathodic half-reactions for electrolysis (Equations 9.3 or 9.4) resulting in electrode corrosion with $H_{2(g)}$ generation. In addition, since some electrode materials show a lower potential for $Cl_{2(g)}$ liberation than oxidation of water to $O_{2(g)}$, one of the cathodic half-reactions for electrolysis (Equations 9.3 or 9.4) may be also coupled with the following anodic half-reaction (Equation 9.6), especially when there is a significant amount of chloride ions in the heating medium, resulting in $H_{2(g)}$ and $Cl_{2(g)}$ generation.



9.4.3 THE GENERATION OF FREE RADICALS

Electron transfer associated with electrochemical reactions at the electrode/solution interfaces leads to the generation of radical species (Schafer, 2001). Konya (1979) described the formations of hydroxyl ($\bullet OH$) and hydroperoxyl ($\bullet OOH$) radicals and hydrogen peroxide (H_2O_2) in oxygen evolution (Equation 9.2) during the electrolysis of water. The cathodic half-reactions of hydrogen generation (Equations 9.3 and 9.4) are also mediated via hydride radicals (H^\bullet) (Sawyer, 2003). Some (hypothetical) mechanisms of generating free radicals by electrolysis and corrosion are illustrated in Figure 9.2.

Since electrolysis and corrosion reactions occur in the micro-environments of the electrodes, the radical species potentially formed under Ohmic heating conditions might be H^\bullet and oxygen-containing free radicals, such as $\bullet OH$, $\bullet OOH$, and superoxide anion radicals ($O_2^{\bullet -}$), as well as molecules like H_2O_2 and singlet oxygen (1O_2). These reactive oxygen species can aggressively attack

causes electrochemical reactions. Thus, I_f can be regarded as a “stray” current and it is essentially a loss of useful electrical energy. Tzedakis et al. (1999) reported that the ratio of I_f/I_c could even be 20–40%. This may occur if faradaic currents are not controlled.

9.5 THE MINIMIZATION OF ELECTROCHEMICAL REACTIONS

While electrochemical reactions at electrode/solution interfaces cannot be completely eliminated during Ohmic heating, it is possible to minimize them.

The capacitive current may be increased by using electrodes with large surface roughness. Scanning electron microscopic analyses indicated that both platinized-titanium (Samaranayake and Sastry, 2005) and DSA (Amatore et al., 1998) electrodes have a large microscopic surface area. It has been further demonstrated that these electrodes yield very low corrosion with low-frequency AC. However, the use of highly porous/rough electrodes for food processing by Ohmic heating may be hindered because of the possibility of harboring tiny food particles, microorganisms, or food macromolecules, such as proteins, in the interstitial spaces within the electrodes. Nevertheless, the high temperatures at such locations may well result in local sterilization, although electrodes may have to be tested periodically to ensure absence of deposits.

9.5.1 PULSED OHMIC HEATING

The most successful method of minimizing electrochemical reactions is the use of high-frequency AC. The electric field is then reversed before saturation of the electrical double-layer capacitors inhibiting the faradaic current. However, the potential use of high-frequency generators for Ohmic heating may be limited by cost considerations. Samaranayake et al. (2005) developed a high-frequency pulsed Ohmic heating technique using IGBT (insulated gate bipolar transistor) power semiconductors. The IGBTs are relatively inexpensive, lightweight, and much smaller in size than high-frequency generators. Since these are rapid switching devices, they enable the application of voltage and current as high-frequency short-duration square wave pulses. Figure 9.3 shows typical pulse waveforms of voltage and current generated by the IGBT. The study by Samaranayake et al. (2005) showed that pulse parameters, such as frequency, pulse width, and delay time (off-time between adjacent pulses) have significant effects on minimizing electrochemical reactions. This study further showed that, as compared to the conventional 60 Hz (sine wave) Ohmic heating, pulsed Ohmic heating is capable of significantly ($P \leq 0.05$) reducing the corrosion of stainless-steel,

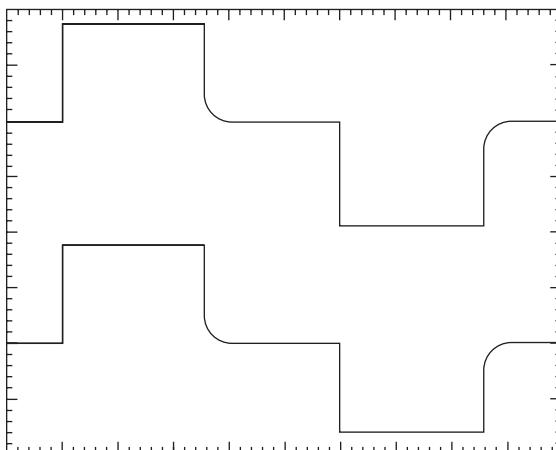


FIGURE 9.3 Typical pulse waveforms of voltage (bottom) and current (top) generated by IGBT.

titanium, platinized-titanium, and graphite electrodes. Pulsed Ohmic heating is also shown to be a promising reheating and sterilization technology for space missions (Jun et al., 2007).

9.6 CONCLUSION

The exploitation of the advantages of Ohmic heating while minimizing the electrochemical reactions represents an interesting challenge. Various methods exist, including the use of high frequencies, high-capacitance electrodes, and IGBT-type pulser units. The electrochemical nature of Ohmic heaters may have beneficial effects, especially in nonfood processing applications.

SYMBOLS

AC	alternating current
DC	direct current
DSA	dimensionally stable anode
IGBT	insulated gate bipolar transistor
e	electron
I_{total}	total current (A)
I_c	capacitive current (A)
I_f	faradaic current (A)

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Section 4

Ohmic Heating Behavior and Design Parameters

10 Ohmic Heating Behavior of Foods

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and Jorge Moreno*

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10.1 OHMIC HEATING OF FOODS: LIQUIDS, SOLIDS, AND MIXTURES

10.1.1 TEMPERATURE DISTRIBUTION

In an Ohmic process, the heating rate of a material depends directly on the conductivity of the element that acts as resistance, which can be liquid or solid. In either form, the temperature distribution in the system turns out to be relatively uniform (except for solid anisotropy). In most cases, the electrical conductivity of foods increases linearly with temperature. The only exceptions occur with components, such as starches, that may undergo phase transitions or significant structural changes during the heating process (Sastry, 2005).

10.1.2 DISTRIBUTION OF THE TEMPERATURE IN MIXED SYSTEMS

A sample that has more than one phase is referred to as a mixed system, such as in the case of a liquid mixture or particles of solid food. The electrical conductivity of all phases must be considered when studying mixed systems, since this property determines the systems' temperature behavior, together with other variables such as particle geometry, size, and the concentration of solids. A current applied to the sample will follow the path that presents the least electrical resistance. In other words, the current flows through the section with higher conductivity, irrespective of its solid or liquid state. The result is that the temperature variations within the sample are directly proportional to its current density.

Sastry and Salengke (2007) studied single-particle systems by varying the electrical conductivity of the medium. They found that when the medium was solid it was less conductive, and overheating occurred in the vicinity of the particle.

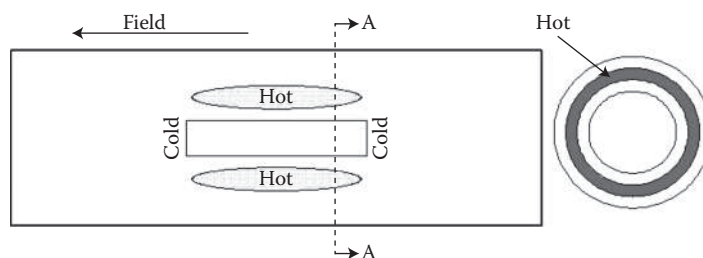


FIGURE 10.1 Static situation; side view on left, section A–A on right, the conductivity of the liquid is higher than the solid. (Sastry, S.K. and Salengke, S. Ohmic heating of solid–liquid mixtures: A comparison of mathematical models under worst-case heating conditions. *Journal of Food Process Engineering*. 2007. 21:441–458. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. With permission.)

At the same time, the low-current density zones prior and posterior (regarding the electric field direction) result in slower heating zones. However, since the total surrounding area is relatively small, the net effect is a more rapid heating of the particle in a static situation (Figure 10.1).

The case when a solid is more conductive is illustrated in Figure 10.2. This shows that low heating occurs in the high-surface-area region, while the prior and posterior sections tend to overheat.

Depending on the type of process and the product characteristics and relevancy, there are different ways to consider the distribution of the temperature in the system. For example, it could be important to characterize the slowest-heating location or the hot spot in the food.

When exploring the cold spot situation, Sastry and Salengke (2007) identified two possible scenarios wherein a single (inclusion) particle is at a lower temperature than its surroundings. Their first case considers an inclusion particle of lower electrical conductivity than its surroundings. This situation has the potential for under processing if the particle is either of small size relative to the heater cross section, or is aligned in such way as to present a minimal cross section to the electric field (Figure 10.3). Under these conditions, the major part of the current effectively bypasses the inclusion particle (bypass scenario). Their second case considers an inclusion particle of higher electrical conductivity than its surroundings. The greatest potential for under processing, in this case, is when the particle is aligned in a way that it represents a significant fraction of the available cross section to the electric field (Figure 10.4). In this situation, a significant part of the current passes through the inclusion particle, but the electric field is weakened in its vicinity (field weakening scenario). The fluid has more under-heated than overheated regions, and consequently convection will tend to increase heating.

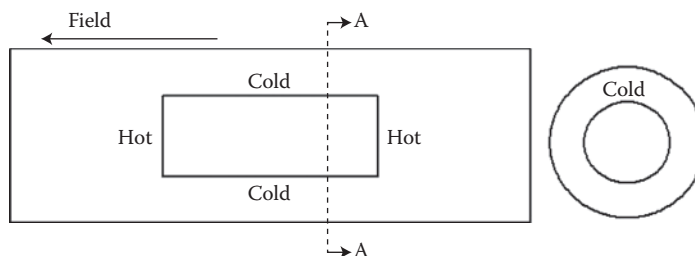


FIGURE 10.2 Static situation; side view on left, section A–A on right, conductivity of the solid is greater than the liquid. (Sastry, S.K. and Salengke, S. Ohmic heating of solid–liquid mixtures: A comparison of mathematical models under worst-case heating conditions. *Journal of Food Process Engineering*. 2007. 21:441–458. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. With permission.)

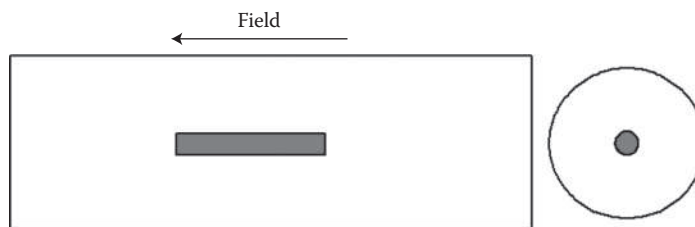


FIGURE 10.3 Worst-case heating scenarios: inclusion particle of lower electrical conductivity than surroundings (current bypass scenarios). (Sastry, S.K. and Salengke, S. Ohmic heating of solid–liquid mixtures: A comparison of mathematical models under worst-case heating conditions. *Journal of Food Process Engineering*. 2007. 21:441–458. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. With permission.)

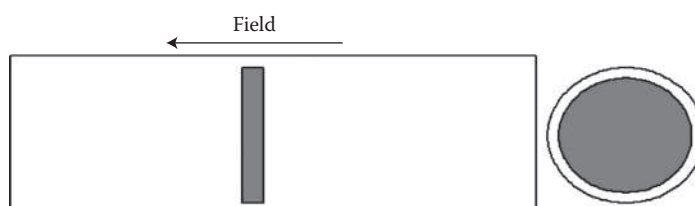


FIGURE 10.4 Worst-case heating scenarios: inclusion particle of higher electrical conductivity than surroundings (field weakening scenario). (Sastry, S.K. and Salengke, S. Ohmic heating of solid–liquid mixtures: A comparison of mathematical models under worst-case heating conditions. *Journal of Food Process Engineering*. 2007. 21:441–458. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. With permission.)

In osmotic dehydration (OD) processes, hot-spot control is critical because the product's temperature must be monitored and controlled to avoid damaging the product's nutritional and organoleptic characteristics. In tests developed regarding OD, it was demonstrated that the worst case is when the product has a higher conductivity (large gap) compared to the conductivity in the solution. This is due to the larger current flow that circulates around the tissue resulting in overheating and internal browning. In addition to the conductivity of the system, they also discovered that the number, size, and position influence of particles involved in the process, directly affected the percent of product weight loss and total solid gain.

10.2 OHMIC HEATING EFFECTS ON FOODS

During Ohmic heating (OH), the electrical current is passed through a food and the resistance it imposes leads to the generation of heat inside the product. OH provides a rapid and uniform heating, resulting in less thermal damage than a conventional heating. The operation allows manufacturers to obtain high-quality products with minimum sensorial, nutritional, and structural changes, and processed foods can be produced in a short processing time (Rahman, 1999).

In OH, the electric field can cause changes in the physical properties and the permeability of vegetable cells below the temperature at which cell membranes are normally permeable. This effect, known as electroporation, is beneficial for accelerating processes of mass transfer in technologies that require heating to preserve foods. OH has been shown to enhance the drying rate (Wang and Sastry, 2002; Zhong and Lima, 2003). Therefore, the combined application of OH with other technologies is a good alternative to generate foods that preserve sensory and nutritional properties of raw materials. In terms of technical development, it is necessary to study some of the constraints and effects on food, such as processing time, physical properties, and microstructure.

10.2.1 PROCESSING TIME

The process time and temperature requirements are the conditions that limit the production of high-quality food. If temperatures are high and processing times are prolonged, there will be adverse effects on the food. Therefore, it is important to consider the use of technologies that apply moderate temperatures and short process times to produce high-quality foods.

The use of osmotic treatments is a widespread practice for removing water from food. OD is considered minimal processing and it preserves the fresh-like characteristics of food. The use of a vacuum in OD maximizes the rate of water loss and solid gain. Mass transfer during OD occurs through the semi-permeable cell membranes of the dominant resistance in biological materials. Cell membrane properties may change from partial to total permeability, leading to significant changes in tissue architecture (Rastogi et al., 2000).

In OH, the electric field strength affects cell membrane permeability and can enhance diffusion through cell walls. For example, water loss has been observed to be greater in apple samples treated at 50°C, especially in combined treatments of OD-OH. Similarly, solids gain was greater in those treatments where OD-OH was applied (Figure 10.5). This is due to the coupled action of different mass transport mechanisms (Moreno et al., 2004).

The increases in temperature, electroporeabilization, and vacuum effect promote a gain of osmotic solution into tissue pores, thus reaching an overall sample concentration with less water loss. Treatments at 30°C suggest a lower process driving force and subsequently longer treatment

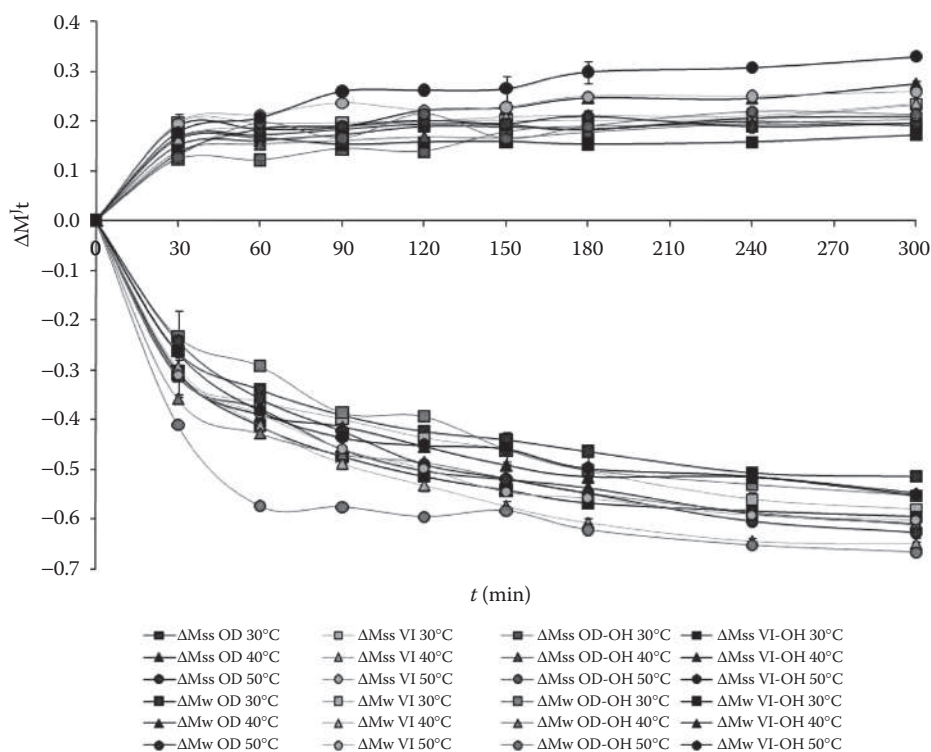


FIGURE 10.5 The effect of osmotic treatments on water content (ΔM_w) and soluble solid (ΔM_{ss}) changes. Atmospheric pressure (OD), vacuum (VI), Ohmic heating (OD-OH) and vacuum-Ohmic heating (VI-OH) treatments were carried out with 65°Brix sucrose solution. (Superscript J becomes w or ss when it refers to water content or soluble solid, respectively.)

times, which may induce a greater number of cell layers to be affected by the osmotic treatment at a determined overall concentration of the sample, consistent with a flatter water concentration profile (Fito et al., 2001).

10.2.2 PHYSICAL PROPERTIES

10.2.2.1 Texture Changes

Texture is one of the main properties that define the quality of preserved food; the loss of the firmness limits a food's acceptability and commercialization. The texture of fruit is based on its cellular structure. Maximum force values obtained from mechanical tests indicated that samples under osmotic treatment showed a decrease in firmness (Table 10.1). The greatest difference was observed in samples treated at atmospheric pressure (OD), especially those tested at 50°C. OD-OH treatments implied the lower force which decreased at 40°C and 50°C.

The application of a vacuum resulted in a greater firmness of fruit by replacing the osmotic solution in the pores caused by air loss, obtaining a more compact and less-deformed tissue than at atmospheric pressure (Moreno et al., 2004). Moreover, it has been reported that when a treatment for a_w reduction is applied, changes in the texture of vegetal tissue are more dependent on physical and chemical changes due to the influence of the transformation of protopectin to soluble pectin and the diffusion of sugar in intercellular spaces, which causes loss of turgor and ion movement through the cell wall into the media (Fito et al., 2001).

10.2.2.2 Color Changes

Color change in fruit is expressed in terms of CIE parameters L, a, and b, individually or in combination, chroma (Cab), hue (Hab), or total color difference (DE) (Table 10.2). Color changes in fruit depend on the processing temperature, medium, and time. In osmotic-treated apples, a 40% decrease in lightness (L^*) was observed in vacuum impregnation (VI) treated samples compared to fresh samples. However, in samples treated with OD and OD-OH, L^* values increased by 5%.

Vacuum impregnation treatments led to lower L values associated with transparency gained from air loss, an effect produced by the total or partial substitution of the air present in the pores by the impregnation solution (Moreno et al., 2004). The a^* and b^* values decreased in VI treatments and increased in OD and OD-OH treatments conducted at 40°C and 50°C compared to fresh apples. When the ΔE (total color difference) was evaluated, the smallest changes were associated with OD treatments and the greatest with the vacuum impregnation (VI). Therefore, the main differences are due to the loss of clarity in line with transparency.

TABLE 10.1

Effect of Osmotic and Ohmic Heating Combined Treatments on the Firmness of Apples

Treatment		Temperatures		
		30°C	40°C	50°C
Fresh		1050.9 ± 123.7 ^a	1050.9 ± 123.7 ^a	1050.9 ± 123.7 ^a
OD	65°Brix	659.1 ± 35.1 ^f	637.5 ± 13.4 ^{d-g}	687.7 ± 77.5 ^{c-e}
OD-OH	65°Brix	705.5 ± 31.7 ^{d-f}	684.2 ± 61.3 ^{d-g}	629.9 ± 26.9 ^{d-e}
VI	65°Brix	678.9 ± 63.5 ^{e-f}	645.7 ± 76.1 ^{e-g}	578.1 ± 12.2 ^{d-e}
VI-OH	65°Brix	779.7 ± 54.8 ^{b-e}	605 ± 56.9 ^{e-g}	594.2 ± 21.7 ^{d-e}

^{a-g} When there are significant differences at 5.0%, homogeneous groups in each variable, according to an LSD test, they are identified by the same superscript letter.

TABLE 10.2**Color Evaluation in Fresh Samples and at the End of Each Treatment**

Treatment		L*	a*	b*	ΔE^*
Fresh		75.5 \pm 1.9 ^f	-7.5 \pm 1.1 ^a	22 \pm 1.8 ^f	0 \pm 0
OD	65°Brix	76.6 \pm 1.7 ^{fg}	-5.2 \pm 0.2 ^b	25.4 \pm 1.1 ^g	4.7 \pm 0.6 ^{a,b}
OD-OH	65°Brix	68.0 \pm 7.5 ^d	-2.3 \pm 0.8 ^{c,f}	18.4 \pm 5.4 ^{c,d}	10.4 \pm 8.3 ^c
VI	65°Brix	42.1 \pm 1.7 ^c	-3.6 \pm 0.6 ^c	16.0 \pm 0.8 ^b	34 \pm 1.9 ^d
VI-OH	65°Brix	41.7 \pm 1.3 ^{a,b}	-2.4 \pm 0.1 ^{c,f}	11.8 \pm 1.3 ^a	35.7 \pm 1.2 ^{d,e}

^{a-g} When there are significant differences at 5.0%, homogeneous groups in each variable, according to an LSD test, they are identified by the same superscript.

10.2.3 MICROSTRUCTURE

The OD of fruit parenchyma by immersion into a sucrose solution affects its microstructure, producing collapsed and deformed cells and intercellular spaces that are lengthened and longitudinally contracted (Quiles et al., 2004). To better understand the effect of OD and OH on texture characteristics at the cell level, an electron microscopy technique was used. Figure 10.6 shows the microstructure of fresh strawberry. A high degree of cell compartmentalization and small intracellular spaces was observed.

The effects of OD, VI, and OD-OH treatments are shown in Figures 10.6 (b, c, and g), respectively. The cells changed their shape and reduced in size during all processes, which may be explained by the native liquid loss. VI samples are affected by vacuum-pulsed application, in Figures 10.6 (c and f) it is possible to observe that thickness of the middle lamella between cells is greater in VI than OD treatments, and cellular breaking by electro-thermal effect can be observed in Figure 10.6 (g, i).

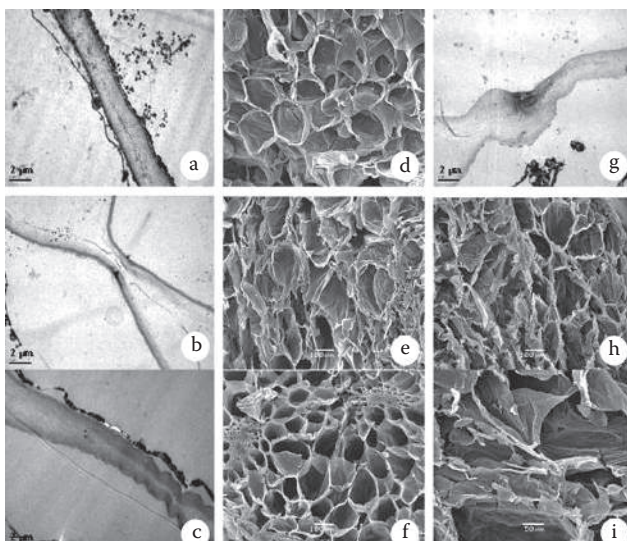


FIGURE 10.6 Electron micrographs of parenchyma tissue from fresh and treated strawberries with 65% (w/w) sucrose solution at 50°C. Fresh control (a and d); OD (b and e), vacuum impregnation (c and f) and OD-OH (g,h, and i). [(a,b,c, and g) obtained TEM and (d, e, f, h, and i) obtained SEM].

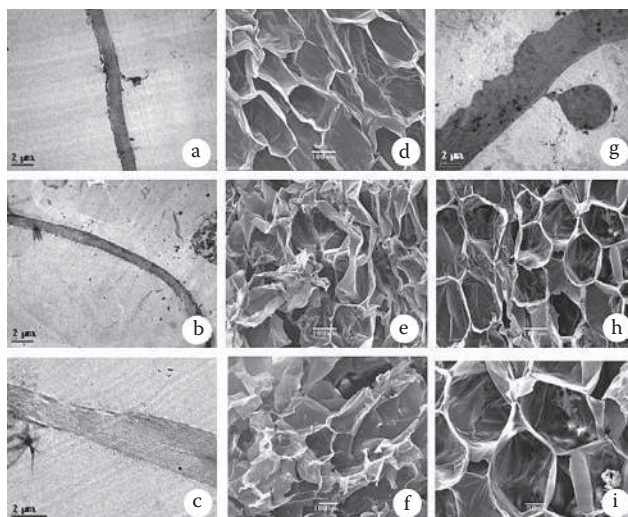


FIGURE 10.7 Electron micrographs of parenchyma tissue of fresh and treated apples with 65% (w/w) sucrose solution and 50°C. Fresh control (a and d); OD (b and e), vacuum impregnation (c and f) and OD-OH (g, h, and i). [(a, b, c, and g) obtained TEM and (d, e, f, h, and i) obtained SEM].

The greater firmness observed in VI samples may be explained by the presence of polymeric material. This material could be a polymeric compound or concentrated sugars, which may be formed by interactions between the middle lamella pectin and the osmotic solution solutes, Figure 10.6 (c, f).

Osmotic and heating processes cause different modifications at cell level according to the type of food, heating, temperature, and application of vacuum on processing between others.

This has been previously observed for osmosed apple slices where the internal cells remained unaltered throughout the osmotic process, whereas in the more external zone a compositional profile is developed coherently with changes in cell structure (Moreno et al., 2004). From this point of view, internal cells in the tissue could remain alive, thus affecting product stability and quality.

In regards to possible differences promoted by the kind of treatment (OD, VI, or OD-OH), these can be observed by different aspects that present the cells, deformations or breakage of the cellular membrane especially by electro-permeabilization effect. In Figure 10.7 (a, d) is depicted the microstructure of fresh apple. TEM and SEM observations allow us to observe the structural solids, such as cell wall and membranes. OD-treated samples (Figure 10.7e) showed a great degree of cell decompartmentation, reflected by the few definitions of the cell walls and membranes observed in micrographs, as compared with the well-preserved cells in OD-OH (Figure 10.7h) and VI-treated (Figure 10.7f) samples. In Figure 10.7 (g, h, and i) the electroporation effect is observed, since it is possible to see the breaking of the cell wall and cellular membrane. These observations agree with the mass transfer behavior commented on above: the major water loss and sucrose gain were observed in OD-OH and VI-OH treatments, respectively.

10.3 OHMIC HEATING EFFECTS ON MASS TRANSFER

10.3.1 DIFFUSIVITY

Diffusivity is one of the most important factors in mass transfer in industrial applications. It is well known that the synergy of electricity and temperature makes this type of heating more efficient. As a result, many authors have been pursuing the application of OH to increase mass transfer into the food materials. Using Ohmic and microwave heating, Wang and Sastry (2002) investigated the

electro-thermal effects on apple juice from preheated apple samples. Sensoy and Sastry (2004) studied the effect of moderated electric field (MEF) processing on permeability. Zhong and Lima (2003), found that the drying rates of Ohmically heated sweet potato samples were faster than raw samples in most treatment combinations. Kemp and Fryer (2007) studied molecular diffusion in model foods under conditions of elevated temperatures and in the presence of alternating electrical fields using the uptake rates of indicator dyes.

Another important study by Praporscic et al. (2006) showed how the degree of tissue disintegration and juice yield in potatoes and apples depends on the field intensity, temperature, treatment duration, and type of plant tissue. Kulshrestha and Sastry (2006) worked on the effect of OH on cell membranes of cellular food material. Jemai and Vorobiev (2002) found that moderated electric field pulses (MEFP) increased the diffusion of soluble substances from apple slices. They found that the diffusion coefficient starts at field intensities of 100–150 V/cm.

Sanjay and Sastry (2007) worked on Chinese water chestnuts. The apparent diffusion coefficient of salt in water chestnuts was not dependent on the concentration of the salt solution and they significantly increased with temperature following the Arrhenius equation. Each of these studies demonstrated the benefits of OH as a new technology.

The study described below was designed to examine the combined effect of temperature and electricity field on the apparent diffusivity of sugar in Granny Smith apples. Through the application of OH and methods described in Sanjay and Sastry (2007), we ran assays on apple slices (average thickness of 1 mm) at three temperatures (30°C, 40°C, and 50°C) at three electric fields (13.3, 18.6, and 24 V/cm). For any given voltage, the data reasonably followed the Arrhenius correlation.

It is important to consider the variability in the apples' cell structure; this variability significantly affected our results. Table 10.3 demonstrates the positive effects of the application of OH in obtaining higher diffusion coefficients. The data obtained confirm that OH is a valid tool for enhancing sugar diffusivity in Granny Smith apples (Figure 10.8).

Although the activation energy of three electric fields (0, 13.6, and 18.6 V/cm) fit a quadratic equation, further work is necessary. At 50°C, we found evident shrinkage in the apple slices and, therefore, we do not recommend this temperature for use in OD coupled with OH. If the goal is an increase in the diffusion coefficient, without large changes in volume, we recommend temperatures between 30°C and 40°C.

TABLE 10.3
Different Diffusion Coefficients of Granny Smith Apples

Temperature	V/cm	Diffusion Coefficient
292.15	0	4.1505E-10
303.15	0	4.60E-10
313.15	0	5.47E-10
323.15	0	9.43E-10
303.15	13.333333	4.49E-10
313.15	13.333333	5.58E-10
323.15	13.333333	1.01E-09
303.15	18.666667	5.70E-10
313.15	18.666667	6.11E-10
303.15	24	5.80E-10
313.15	24	6.43E-10
323.15	24	1.23E-09

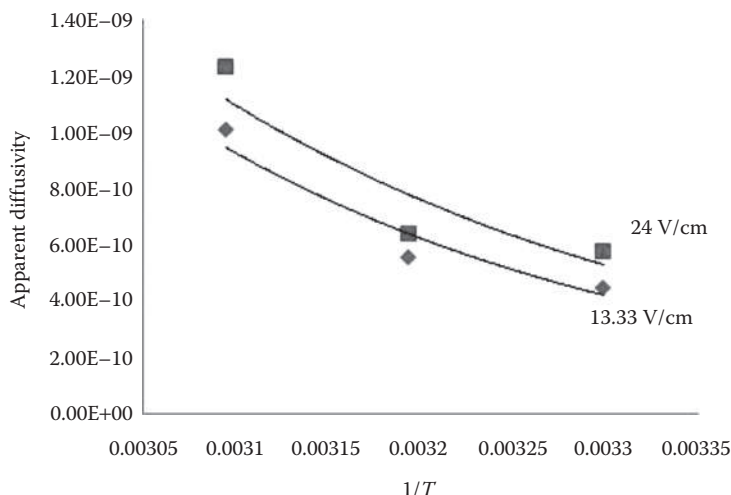


FIGURE 10.8 Temperature versus apparent diffusion at different electric fields.

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11 Electrodes in Ohmic Heating

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and Hosahalli S. Ramaswamy*

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11.1 INTRODUCTION

Ohmic heating is one of the novel thermal process technologies that involve pasteurizing or sterilizing food products by passing alternating electric current using food as a medium. The electrical resistance property of the food causes the power to be translated directly into volumetric heating. In the past the technology was used to pasteurize milk, but due to lack of inert materials for electrodes (Mizrahi et al., 1975), high processing costs (De Alwis and Fryer, 1990) and Faradaic effect, it was abandoned for some time. Lately, however, Ohmic heating has gained resumption due to the availability of a sufficient power supply, corrosion-resistant electrodes, and the production of high-quality products as compared to conventional thermally processed products. The advancement in technology of electrode production and the power supply contributes to the renaissance of Ohmic heating technology in food preservation areas. The desired electric current from the source to the food is transmitted by metal electrodes, which are designed for that specific purpose. The inertness and electrical conductivity of the electrodes are the determining factors to accomplish the desired process and production of safe food, free from any forms of contaminants. Therefore, the focus of this chapter is to discuss common electrodes used and associated effects in the Ohmic heating process.

11.2 COMMON ELEMENTS/COMPOUNDS USED FOR OHMIC HEATER ELECTRODES

11.2.1 CARBON/GRAPHITE

Carbon has two natural crystalline allotropic forms: graphite and diamond. Diamond is among the hardest materials known, while graphite is soft enough to form a streak on paper. Each has its own distinct crystal structure and properties. Graphite is unique in that it has properties of both a metal and a nonmetal. It is flexible but not elastic, has a high thermal and electrical conductivity. Among allotropes of carbon, graphite is commonly used for making electrodes. Pure graphite is one of the most chemically inert materials. It is resistant to most acids, alkalis, and corrosive gases. However, impurities are almost always present to some degree in both natural and artificial graphites and often have an important catalytic effect with a resulting increase in the chemical reactivity (Pierson, 1993). Due to this, the use of graphite as an electrode is limited by its tendency to facilitate pitting corrosion in some stainless steel (ASM, 2006).

11.2.2 ALUMINUM

It is the most widely used nonferrous metal in food processing equipment manufacturing. Pure aluminum is a silvery-white metal with many desirable characteristics. A few of its useful characteristics are: it is not soluble in water under normal circumstances, a high strength-to-weight ratio, a nonmagnetic property, and good thermal and electric conductivity. The metal has a remarkable ability to resist corrosion due to the phenomenon of passivation and its low density. Passivation is the ability of the element or compound to form an impervious surface coating, which inhibits corrosion. Its corrosion resistance behavior is excellent due to a thin surface layer of aluminum oxide that is formed when the metal is exposed to air, which effectively prevents further oxidation. Its electrical conductivity is about two-thirds of copper, making it economical for power transmission. This metal is used for different functions and is also used as an electrode in Ohmic heating (Mizrahi et al., 1975; Uemura et al., 1994). The strength of an aluminum alloy is greater than that of the pure metal, but their resistance to corrosion is lower and hence, it is not commonly used in food-processing equipment (Sinnott, 1996).

11.2.3 STAINLESS STEEL

Stainless steel is the term used to describe an extremely diverse family of iron-based engineering materials, which are selected primarily for their corrosion and heat resistance. Stainless steel does not stain, corrode, or rust as easily as compared to ordinary steel, but that does not mean that it is completely stain-proof (Fendorf, 1995). Stainless steel differs from carbon steel by the amount of chromium present and other elements, like nickel and molybdenum. Carbon steel rusts when exposed to air and moisture as compared to stainless steel.

High-grade stainless steel is the most important type of steel used in direct contact with food and commonly used in constructing food-processing equipment. All stainless steels contain principally iron and a minimum of 10.5% chromium. The chromium forms a passivation layer of chromium (III) oxide (Cr_2O_3) when exposed to oxygen. The passive film of chromium oxide prevents surface corrosion and blocks corrosion from spreading into the metal's internal structure. This improves the hardness and abrasion resistance of the alloy. Corrosion resistance can, however, be adversely affected if the component is used in a nonoxygenated environment (Ashby and Jones, 1998).

There are over 150 grades of stainless steel, however, in food equipment manufacturing, two types of stainless steels are used, AISI 304 and AISI 316. The latter is about 25% more corrosion resistant than the former (Saravacos and Kostaropoulos, 2002). Unlike other grades, this grade contains molybdenum and nickel and can be categorized in the family of duplex steels (Table 11.1). The addition

TABLE 11.1**Family of Stainless Steels with Their Chemical Composition and Corrosion Resistance Nature**

Family	Chromium %	Nickel %	Molybdenum %	Others	Remark
Ferritic	12.5–17	—	—	Iron and very little carbon	Superior corrosion resistance to martensitic stainless
Martensitic	10.5–18	—	—	Iron, very less carbon	Moderate corrosion resistance
Austenitic	16–26	6–12	—	Iron, very less carbon	Superior corrosion resistance to both ferritic and martensitic
Duplex steels	18–26	4–7	0–4	Iron and copper carbon <0.03%	Provides a combination of the corrosion resistance of austenitic stainless steels with greater strength

of molybdenum prevents specific forms of corrosion and improves the alloy properties at a higher temperature which is important in welding (Perry and Green, 1997). It is also known as marine-grade stainless steel due to its increased resistance to chloride corrosion compared to type 304. Furthermore, the addition of nickel improves the toughness and improves the properties at low temperatures. Both types of these electrodes are resistant to acid and lye solution and, hence, HNO_3 and NaOH solutions may be used for their cleaning purpose, but they are not resistant to halogens (Cl), which can cause pitting especially at higher temperature and low pH values (Saravacos and Kostaropoulos, 2002).

11.2.4 TITANIUM

Titanium is one of the periodic table elements with an atomic number of 22 and molecular weight of 47.867 g/mol. Titanium is a low-density, strong, lustrous, corrosion-resistant transitional metal with a silver color. The two most useful properties of the metal are corrosion resistance and the highest strength-to-weight ratio of any metal (Donachie, 1988). Titanium is nonmagnetic and has good heat-transfer properties. It has the ability to passivate and thereby exhibits a high degree of immunity against attack by most mineral acids and chlorides. Commercially pure titanium satisfies the basic requirements for corrosion service (Donachie, 2000). In its unalloyed condition, titanium is as strong as some steels, but 45% lighter (Barksdale, 1968). The most noted chemical property of titanium is its excellent resistance to corrosion; it is almost as resistant as platinum, capable of withstanding attack by acids and moist chlorine in water, but is soluble in concentrated acids (Casillas et al., 1994). This metal forms a passive and protective oxide coating (leading to increased corrosion resistance) when exposed to elevated temperatures in air, but at room temperatures it resists tarnishing. Tarnish is a thin layer that forms over metals and other semi-reactive metals as their outermost layer undergoes a chemical reaction.

11.2.5 PLATINUM

As a pure metal, platinum is silvery-white in appearance, lustrous, ductile, and malleable. It is resistant to chemical attack. It has excellent high-temperature characteristics and stable electrical properties. These properties of platinum are exploited for industrial applications. It does not oxidize at any temperature, and is resistant to corrosion, but it is corroded by halogens, cyanides, sulfur, and caustic alkalis. Due to its resistance characteristics for corrosion, platinum has many uses. It is well-suited for making fine jewelry, and its alloys are used in surgical tools, laboratory utensils, electrical-resistant wires, and electrical contact points. Platinum and platinum's alloy with titanium

and nickel are also used as electrodes for Ohmic heaters. It expands at nearly the same rate as soda-lime-silica glass, so it is used to make sealed electrodes in glass systems. Platinum-resistant wires are used in high-temperature electric furnaces. Platinum anodes are used in cathodic protection systems to prevent ships, pipelines, and steel piers from corroding in salt water.

11.3 THE PROPERTIES AND FUNCTION OF ELECTRODES IN OHMIC HEATING

Thermo-physical and chemical properties, as well as cost of electrodes are very important factors in design, construction, and application of electrodes in Ohmic heating. The material used in construction of the electrode must have the following properties: (i) high resistance to corrosion, (ii) high electrical conductivity, (iii) high resistance to acid foods (iv) conducive thermal properties, (v) high mechanical strength, (vi) yield easily for fabrication and repair, (vii) low cost and easy availability. The first two are the major properties that determine inertness and efficiency of the electrodes during heating process, respectively. Resistance to corrosion is very important in food processing since the majority of foods are rich in moisture and involve heating. Furthermore, the corrosion rate is high in low pH foods. Most often pitting is the most common type of corrosion of electrodes which results in the formation of thin holes on the surface of the electrode as compared to uniform corrosion. Due to this reason corrosion-resistant materials are used to minimize the contamination risk of the food from traces of electrodes. On top of this, electrical and thermal properties play a role in discharging the supplied voltage and enhancing the volumetric heating rate. Electric current supplied by electrodes flows in the system of food (in static or continuous flow condition) and is absorbed equally by both liquid and particles, provided that they have the same electrical conductivity, ideally without loss of electric current in any form. During heating, the temperature of the food will increase and thereby increase its electrical conductivity. On top of this, mechanical strength, cost, and availability of electrodes in the market are additional factors that enable us to make a rational decision in the choice of electrodes.

The need for fast heating of most heat-sensitive products has led to the development of the heat-generation process, which is based on the conversion of electric energy from alternating electric source into heat within food. Therefore, the main function of the electrodes in Ohmic heating operations is to pass electric current to the food for volumetric heating process. Heating is a function of electric resistance of a food and applied electrical potential. Commonly, low-frequency alternating current (50–60 Hz) is supplied to the Ohmic heating column which consists of 2–6 electrodes depending upon the design of the heater. The electrodes are separated by spacer tubes which serve as an insulating device. Even though Ohmic heating can be used for various types of foods, due to its uniform heating nature Ohmic heating is very suitable for heating of particulate foods, since both the liquid and particles can be heated at the same time (Sastry, 1992).

11.4 TYPES OF ELECTRODES USED IN OHMIC HEATING OF FOODS

Since the discovery of Ohmic heating as one of thermal food processing technologies, different types of electrodes have been used for various types of products. One of the first attempts to use electricity for milk pasteurization and to improve consumer health was performed by the application of a 220–420 V alternating current using carbon electrode (Getchell, 1935). Three years later the same electrode was used to pasteurize milk (Moses, 1938). Due to the presence of impurities in carbon electrodes and their tendency to enhance reactivity and pit corrosion, scientists have been looking for other more corrosion-resistant materials. Even in recent years graphite electrodes have been used for pasteurization of orange juice (Shirly and Eyal, 2005).

In addition to graphite electrodes, aluminum electrodes were used to test the effect of blanching vegetables (Mizrahi et al., 1975), the effect of electrical frequency on the heating rate of fish protein (Uemura et al., 1994), and microbial inactivation in tomato puree (Onwuka et al., 2008). With the development of science and technology, more corrosion-resistant metals and alloys are

used to overcome the main problem associated with the corrosion of electrodes. Stainless steel is one of the most commonly used and relatively cheaper electrodes, which have been used by different scientists to evaluate the effect of Ohmic heating on different food processing application areas. Stainless-steel electrodes are used to evaluate the thawing effect of Ohmic heating on frozen shrimp (Balaban et al., 1992); blanching effect on vegetables (Mizrahi, 1996), pea puree (Icier et al., 2006), and cauliflower (Eliot et al., 199); inactivation of *Lactobacillus acidophilus* (Cho, 1996), *Bacillus subtilis* (Cho, 1999); heating (pasteurization/sterilization) of apple and sour cherry (Icier and Ilicali, 2004), fruit puree (Icier, 2005), milk (Fillaudeau et al., 2006), fruit juices (Singh et al., 2008; Icier et al., 2008); and for cooking of tofu (Wang, 2007), whole beef muscle (Zell et al., 2009), turkey meat (Zell et al., 2010), and ground beef (Hayriye and Icier, 2010).

Nowadays more corrosion resistant, but expensive, electrodes of platinum, titanium, and their alloys are being used in various types of Ohmic heating equipments. Platinum electrodes were used to investigate the heating rate of fish protein (Uemura et al., 1994) and inactivation of *Saccharomyces cerevisiae* (Guillou and ElMurr, 2002). As compared to the use of platinum electrodes, the titanium electrode was widely used to evaluate extraction efficiency of Ohmic heaters on turnip tissue (Lima et al., 1999), the effect on the behavior of hydrocolloids (Marcotte et al., 1998), bacteria and yeast inactivation in Kefir (Mainville et al., 2001), enzyme inactivation of different foods (Castro et al., 2004), oil extraction from rice bran (Lakkakula, 2004), pasteurization of strawberry juice (Castro et al., 2004), thawing of surimi (Miao et al., 2007), microbial inactivation and protein denaturation of milk (Castro et al., 2008).

Furthermore, an alloy of platinum–titanium (platinized-titanium electrode) was used to investigate the effect of Ohmic heating on the blanching of vegetables and chicken meat (Sarang et al., 2007), and pasteurization of goat milk (Pereira et al., 2008).

Generally, stainless-steel and titanium electrodes are the most commonly used ones in Ohmic heating as compared to others. The platinum electrode is more costly and graphite is more susceptible to corrosion; due to these reasons they have limited application.

11.5 ELECTROCHEMISTRY IN OHMIC HEATING

Electrochemistry is a branch of chemistry involving the study of chemical reactions that take place in a solution at the interface of an electron conductor (electrode) and an ionic conductor (the food), and which involve electron transfer between the electrode and the electrolyte. Electrodes in Ohmic heating can be considered as a connecting point between a current feeder and a liquid-state conductor (food) and they play a vital role by passing on the current uniformly into the food. In order to generate heat in an Ohmic heating system, an electric field or voltage distribution must be applied to the food. The applied electric field is a function of nature and system geometry of the electrode, electrical conductivity of the food, and the applied voltage (de Alwis and Fryer, 1990). Furthermore, the electrical conductivity of the food determines the degree of heating rate. Eventually heat generated due to current flow and resistance of a food enhances the chemical reaction at the electrode–food interface.

11.5.1 ELECTRODE–FOOD INTERFACE INTERACTION

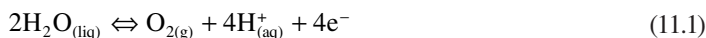
As indicated in the above section, during Ohmic heating there is a direct contact between electrodes and a food. It is important to understand the characteristics of the electrode–food interface interactions during Ohmic heating time in order to understand the electrochemical behavior of Ohmic heaters. The theory of interfacial electrochemistry tells us the electrode–food interface is equivalent to the parallel combination of the resistor (voltage source) and a capacitor (a part that consumes energy) (Rubinstein, 1995). During this interaction phase, the electronic property of the surface of electrode is changed with the application of electric voltage and temperature. This will be done by either supplying or withdrawing electrons via an external source of voltage.

Hence, the release of electrons from the electrode is the main reason for the occurrence of corrosion pits or surfaces on the electrodes. Like a binary common reaction process between two chemical components, the same thing happens in electrode–food interface of Ohmic heating electrodes. On the surface of the electrode, at the electrode–food interface the following reaction is taking place:

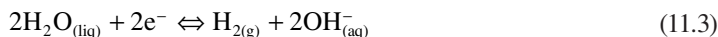


From an electrochemistry viewpoint, both the physical and chemical properties of electrodes are important factors to determine the reaction rate at the electrode–food interface. The possibility of electrochemical reactions occurring at the electrode–food interface during Ohmic heating has been described well in Stirling (1987). The understanding of both electrode kinetics (due to electron transfer) and mass transfer and deposit are essential points to understand interfacial electrochemistry between food and electrodes of Ohmic heating. The reaction of organic molecules of the food and inorganic molecules of the electrode are the two major chemical reactions happening on the interface. The reaction involves an electron transfer to or from molecules or ions of the electrodes and food solution by changing the oxidation state due to the applied voltage and heat generated. Ohmic heating as an electrochemical cell, the electrode where oxidation occurs (where electrons are donated to the electrodes) is called the “anode” and where the electrode reduction occurs (where electrons are accepted from electrodes), is called the “cathode.” These oxidation–reduction sites together make up a corrosion cell on the surface of the electrodes. The anodic process is the direct cause of damage to metallic structures, but both an anodic and a cathodic process must occur for a corrosion cell to be formed. The overall anodic and cathodic half-reactions of electrolysis are expressed as (Samaranayake et al., 2005):

Anodic half-reaction:



Cathodic half-reaction:



Overall electrolysis reaction:



During the heating process as observed in the above anodic and cathodic reactions, the reaction processes can be manifested by the liberation of gases and color changes of electrodes due to corrosion. According to Zhao and Kolbe (1999, p. 84) electrode corrosion caused by Ohmic heating appeared as a light-brown thin porous film and they hypothesized that the “gas bubbles are the results of either water boiling due to localized high current densities or the outgassing by-products of various oxidation-reduction reactions (e.g., H_2 or O_2).”

On the electrode surface, depending upon the nature of the electrode used, a particular electrochemical reaction may occur very fast, slow, or not at all. Such information about electrodes under Ohmic heating conditions is, therefore, important to avoid or inhibit the electrochemical reactions by choosing appropriate electrode materials.

11.5.2 THE EFFECTS OF ELECTRODE CORROSION IN OHMIC HEATING

Foods as biological materials have more complex and interacting thermal, electrical, chemical, physical, structural, and optical properties. These properties play a significant role during thermal processing operations. The moisture and chemical composition of a food play a significant role in determining the rate of the electrochemical process occurring on the electrode–food interface while applying electrical current. Once the electrically induced chemical reaction between the food and electrode is initiated, there will be an occurrence of additional secondary chemical reactions. The reaction rates are dependent upon the nature of the electrode, chemical composition of the food, pH level, applied AC frequency, current density, and other factors.

Although the problems of electrochemical reactions and corrosion are well known in other application fields, very little attention has been paid to the problems related to food processing in Ohmic heating systems. As indicated before, the main function of the electrodes in Ohmic heating is to convey electric current to the food material to be heated. The passage of electric current through an electrically conductive food material obeys Ohm's law ($V = IR$); and heat is generated due to the electrical resistance of the food. During energy transfer between electrode–food interfaces, possible Faradaic reactions taking place at the interfaces may result in partial electrolysis of the solution or electrode corrosion, either via direct metal corrosion or through the electrochemical generation of corroding chemicals. According to Liu et al. (2007) three factors are directly related to the Ohmic heating electrode corrosion: the conductivity of the electrode, the electrochemical stability, and the spark or plasma generation. The corrosion rate will be high with low conductivity, poor electrochemical stability, and high sparking. Some of the effects of this electrolytic process on the food and electrodes are indicated in Amatore et al. (1998).

For instance, during heating, as indicated before, electrode corrosion occurs mainly through electro dissolution induced by the low-frequency AC. For metallic electrodes (M), a generalized anodic half-reaction for the electrode corrosion can be written as follows:



The metal ions (Mn^{+}) corroded and migrated into the heating medium are basically contaminants and may have some toxic potential. Different degrees of corrosion of electrodes and apparent electrolysis of the heating medium have been observed with almost all the types of electrodes. The amount and the chemical nature of the corrosion products migrating into the food during the application of electrical power significantly determine the degree of contamination and safety of the food. This mainly depends upon frequency of electric current applied, type of electrode, and pH condition of the solution. The effect of electric frequency is discussed in Section 11.5.5 and the effect of pH on the corrosion of surface elements of different electrodes is indicated in Table 11.2.

Electrode corrosion has many serious economic, health, and technological consequences.

Pitting corrosion has been very often observed in electrodes used for Ohmic cooking of food products, and due to this reason electrochemical reactions at electrode–food interfaces are considered undesirable during Ohmic heating of food (Samaranayake and Sastry, 2005). Electrodes used in Ohmic heating as compared to other common types of metal electrodes are relatively more expensive. Particularly, platinum electrodes are even more expensive than gold. Hence, the economic damage of corrosion is significant when there is fast corrosion of electrodes.

Furthermore, the heterogeneous polyhydroxy nature of foods facilitates the migrated metal ions to be entrapped in the structure or result in formation of various coordination complexes with their functional groups. Those metal complexes typically have characteristic colors and, therefore, they may alter the color and chemical properties of the processed foods. It is also known that some transition metal ions have catalytic effects for certain food reactions and may facilitate rapid lipid oxidation. Therefore, the electrode corrosion may have an impact on flavor and the overall quality of the processed food products. This problem becomes particularly crucial in food processing,

TABLE 11.2

Comparison of Corrosion Rates (in ppb kJ^{-1}) of the Electrode Materials in an Aqueous Medium

Electrodes	AC Frequency (Hz)	Voltage (V)	Elements Analyzed	Corrosion of Electrodes		
				pH 3.5	pH 5.0	pH 6.5
Titanium, (7.5 cm \times 5.2 cm)	60	110	Ti	0.26 ^b (0.21) ^a	0.03 ^b (0.01)	0.05 ^b (0.03)
Stainless steel (316), (7.5 cm \times 5.2 cm)	60	110	Fe	14.20 ^c (1.95)	8.33 ^d (0.30)	11.43 ^{c,f} (1.51)
Platinized-titanium (7.5 cm \times 5.2 cm)	60	110	Pt	0.25 ^b (0.10)	0.07 ^b (0.04)	0.05 ^b (0.02)
Graphite (7.5 cm \times 5.2 cm)	60	97(\pm 1)	C	26.6 ^e (2.2)	7.2 ^d (0.0)	8.4 ^{d,f} (1.1)

Source: From *Journal of Electroanalytical Chemistry*, 1(577), Comparison of corrosion rates (in ppb kJ^{-1}) of the electrode materials in aqueous medium, 125–135, Copyright 2005, with permission from Elsevier.

^a Values within parentheses indicate standard deviations of mean ($n = 3$) corrosion rates.

^{b–f} Means with different letters are significantly different ($P \leq 0.05$).

where biological molecules naturally present in harmless forms in food may result in poisonous or carcinogenic matters, or bring bad taste or discoloration into the processed food through their electrochemical reduction or oxidation reaction after they combined with released electrode elements (Amatore et al., 1998).

Table 11.2 indicates some of the surface elements of particular electrodes can migrate to the food. In addition to these elements, chromium and aluminum can also be corroded from stainless-steel and aluminum electrodes, respectively. Chromium and aluminum naturally occur in foods and can also leach into food from cookware, utensils, and wrappings, but studies to date have shown that the amount leached from these sources is generally negligible. However, the leaching from electrodes of an Ohmic heater due to the effect of corrosion may outsmart the minimum threshold level recommended for safe consumption and can cause serious health problems. For instance, the daily intake recommendation of aluminum is 8 and 1 mg per day for adults and infants (Health Canada, 2010) respectively. From a health point of view, excess dosages are confirmed toxic; it can cause neurotoxicity and is associated with altered functions of the blood–brain barrier (Banks and Kastin, 1989). It is also indicated that excessive dosages of the element increases estrogen-related gene expression in human breast cancer cells cultured in vivo (Darbre, 2006). Furthermore, due to its 10–30 times concentration of the element in Alzheimer's patients, the metal element is considered as a cause of Alzheimer's disease (Health Canada, 2010).

For most people, eating food that contains chromium (III) is the main route of chromium uptake. Various ways of food preparation and storage may alter the chromium contents of food. Leached chromium (III), has a low solubility in water and readily precipitates as $\text{Cr}(\text{OH})_3$ under alkaline or even slightly acidic conditions (Rai et al., 1987). Even if chromium (III) is an essential nutrient for humans, the uptake of too much chromium (III) can cause health effects. Chromium (III) picolinate is sold as a nutritional supplement to prevent or treat chromium deficiency. However, excessive uptake of it more likely causes DNA damage as compared to other forms of trivalent chromium (Chaudhary et al., 2005). Therefore, the degree of element corrosion from a stainless-steel electrode should be strictly controlled. In addition to this, iron is the principal metal element to make stainless-steel electrodes. During the corrosion of stainless-steel electrodes this metal element also leaches into food with chromium. Even if it is an important mineral in the diet for cell growth,

oxygen transports, DNA synthesis, and good health, too much iron in the system can become toxic and cause numerous health problems. Even a small amount of excess iron can damage the heart and brain and other storage sites in the body and can lead to a heart attack or stroke. Unless we control the level of iron that we consume, the body has no natural way to rid itself of excess iron, so extra iron is stored in body tissues, especially the liver, heart, and pancreas. Severe iron overload, which causes liver and heart damage, can occur in people who are genetically susceptible; this is called hemochromatosis. Hemochromatosis, also called iron storage disease, or bronze diabetes, is an inborn metabolic defect characterized by an increased absorption of iron, which accumulates in body tissues.

As compared to the previous metal elements, the corrosion rate and health effect of platinum and titanium electrodes or their alloys is not significant. Platinum as a metal is not very dangerous; FDA and other countries have reviewed the issue and found no evidence to suggest toxicity *in vivo* (FDA, 2010). The corrosion rate of this electrode is less in different operating conditions and even better than titanium electrodes. Elemental titanium and titanium dioxide is of a low order of toxicity. There is no information available concerning the biological role of this element in the human body. However, dust inhalation may cause tightness and pain in the chest, coughing, and difficulty in breathing.

Corrosion of elements from electrode surface as a pit or surface corrosion, governed by several factors, will have potential deleterious communicative effects with extended Ohmic heating processes. Therefore, the excessive corrosion and accumulation of the metal elements from electrodes during Ohmic heating processes should be acknowledged and the control mechanism should be devised to minimize the rate.

11.5.3 ELECTROLYTE CONTAMINATION AND SAFETY IN OHMIC HEATING

Most food formulations subjected to Ohmic heating contain more than 50% water. During conventional Ohmic heating, the low-frequency (50 or 60 Hz) AC induces electrolysis of water and generates H_2 and O_2 gases at the electrode–food interfaces. The corresponding anodic and cathodic half-reactions and the overall electrolysis reaction are indicated from Equations 11.1 through 11.4. Molecular oxygen generated by electrolysis can oxidize almost all the oxidizable food components, particularly lipids and vitamins like ascorbic acid (vitamin C). The molecular oxygen is also involved in electrode corrosion, or in the formation of insulating species on the electrode surfaces, thereby partially passivating the electrodes (Tzedakis et al., 1999). The liberation of gas bubbles at the electrode–food interfaces does not necessarily indicate the overall electrolysis reaction (Equation 11.3). Sometimes the anodic half-reaction for electrode corrosion (Equation 11.1) may be accompanied with one of the cathodic half-reactions for electrolysis (Equation 11.2 or 11.3), resulting in electrode corrosion with H_2 (g) generation. Because of the high flammability and explosive nature, uncontrolled liberation of hydrogen gas might pose safety concerns in a large-scale continuous Ohmic heating practice. In addition to these, there is a possibility of liberation of Cl_2 (g) from chloride-rich foods (Equation 11.6), especially when there is a significant amount of chloride ions in the heating medium.



11.5.4 THE GENERATION OF FREE RADICALS DURING OHMIC HEATING

A free radical is any atom or molecule that has an “unpaired electron” in the outer ring or shell. An “unpaired electron” will always mean that there is an odd number, since “pairing” of electrons goes by 2s. Since electrons have a very strong tendency to exist in a paired, rather than an unpaired state, free radicals indiscriminately pick up electrons from other atoms, which in turn convert those other atoms into secondary free radicals, thus setting up a chain and propagating reactions which can cause substantial biological damage.

Damaging effect of radicals on macromolecules of our body and the theory of aging has been associated with the reaction of radicals generated due to different factors during food preparation and storage time. Cell membranes of organisms are made of an unsaturated lipid bilayer. The unsaturated lipid molecules of cell membranes are particularly susceptible to damaging free radicals and readily contribute to the uncontrolled chain reaction. If the cell wall is hardened (lipid peroxidation) then it becomes impossible for the cell to properly get its nutrients, get signals from other cells to perform an action, and many other cellular activities can be affected. In addition to this, other biological molecules are also subjected to damage, including RNA, DNA and protein enzymes, vitamins, phenols, phenolic compounds, and other antioxidants. The overall effect of these reactions results in bad effects on health, aggravates the aging process of organisms (Reiter et al., 2001; Wickens, 2001), and affects the shelf-life of processed products. Due to the above reasons, the formation and presence of free radicals in food during food processing or storage time is not required. Therefore, the formation of the radicals should be inhibited or reduced to the minimum levels that do not cause detrimental health effects.

Food as an organic material has different electro activity and effects to change the electrode capacitances (Fiedler and Schols, 2010), which have an effect on the formation of various forms of free radicals. The type of food subjected for Ohmic heating determines the type and level of radicals generated. The major portion of food products processed using Ohmic heating is water. In alternating polarity of electric current, water undergoes an electrochemical reaction and results in the formation of hydrogen and oxygen molecules (Tzedakis et al., 1999).

During Ohmic heating, depending upon the chemical composition of the food and intensity of the electric field applied, at the electrode–food interface, different forms of electrochemical reactions can take place. Electron transfers associated with electrochemical reactions at the electrode–food interfaces leads to the generation of free radical species (Schafer, 2001). Sawyer (2003) also indicated the possibility of formation of radicals during electrochemical reactions at electrodes–food interfaces. The formation of hydroxyl ($\cdot\text{OH}$), hydroperoxyl ($\cdot\text{OOH}$) radicals, and hydrogen peroxide (H_2O_2) in oxygen evolution during the electrolysis of electroheating processes are reported in Konya (1979) and Tzedakis et al. (1999). Samaranayake (2003) in his work indicated that, H^\cdot , $\cdot\text{OH}$, $\cdot\text{OOH}$, superoxide anion radicals (O^\cdot), H_2O_2 and singlet oxygen ($^1\text{O}_2$) are major radicals and oxidizing agents that were formed during Ohmic heating. In addition to this, the reduction of oxygen may lead to the formation of superoxide anion (O_2^\cdot) and free radicals, such as hydroxyl ($\cdot\text{OH}$) due to Fenton's reaction (Tomat and Rigo, 1979).

Ohmic heating as an electroheating technology that involves an electrochemical reaction and the possible occurrence of such types of free radicals is evident. So far limited studies have been conducted to indicate the degree of occurrence of free radicals during the Ohmic heating of foods and there is no sufficient information available to support the danger of free radicals in Ohmically heated foods. However, their occurrence and their detrimental effects (if any) can be minimized by the antioxidants present in foods and through applying high frequency electric field (Liu et al., 2007) respectively. Furthermore their highly oxidative property can be taken as an antimicrobial agent in the food to control the growth of microorganisms.

11.5.5 ELECTROCHEMICAL REACTIONS AND ALTERNATING CURRENT FREQUENCY

Current and voltage, both in AC circuits oscillate as a wave at a certain frequency. The rate of changing direction is called the frequency of the AC and it is measured in hertz (Hz), which is the number of forwards–backwards cycles per second. Because of this, the double-layer capacitors of the electrode–food interface, charges and discharges periodically when AC is applied to an electrolytic cell. Those reactions involve simultaneous cathodic (i.e., reduction) and anodic (i.e., oxidation) half-reactions and the overall reactions produce periodic concentration changes of redox species at the electrode surfaces. The extent of those chemical changes primarily depends upon the frequency of the applied AC signal and the chemistry of the electrolytic cell.

Electrochemical phenomena induced by AC were first reported in the early nineteenth century, and it was a common difficulty encountered in measuring the conductivity of electrolytes. Shaw (1950) was the first person who observed and reported when an alternating current is applied to an electrolytic cell, the cell shows both dissipative and reactive characteristics. Seven years later the corrosive effect of low-frequency (50 Hz) alternating currents (in concentrated acid solution) on stainless-steel, platinum, and gold electrodes were reported to be lower at frequencies greater than a few kHz (Bently and Prentice, 1957). Kulman (1961) also reported that AC-induced electrolysis was closely associated with the corrosion of electrodes. Venkatesh and Chin (1979) studied the effect of a sinusoidal AC electric field on an electrode solution and corrosion of metals in electrolytic cells, and found that a direct current (DC) is generated at each of electrode surfaces and the current is related to the amplitude of the applied voltage signal. The association of the corrosion rate and the frequency of applied voltage is also indicated in the researches performed by Venkatachalam et al. (1981), Lalvani and Lin (1994, 1996), and Bosch and Bogaerts (1998).

All the above reports confirm the effect of AC frequency on a degree of corrosion of electrodes in electrochemistry phenomena. In the case of Ohmic heating, since an Ohmic heater is considered an electrolytic cell the same phenomenon is happening in electrode–food interfaces. Typically, Ohmic heaters are powered by low-frequency (50–60 Hz) AC coming from the public utility supply, because that minimizes the cost and power supply complexity. Under such alternating frequencies, a part of the current passing through the electrode–food interfaces causes an electrochemical process. This electrochemical process is one of the factors not desired during Ohmic heating. This is because the corrosion rate of electrodes due to electrolyte reaction when AC electrical frequencies below 500 Hz and at current density up to 3000 A/m² (Reznick, 1996; Wu et al., 1998) are higher than at higher frequencies. In conventional Ohmic heaters with a low frequency (50–60 Hz) of AC, the corrosion of electrodes and partial electrolysis of the solution are commonly observed in Ohmic heating processes (Amatore et al., 1998; Tzedakis et al., 1999). This low-frequency level possibly enhances the Faradaic reaction rate at the interface and possibly results in electrolysis of the solution and metal corrosion (Bosch and Bogaerts, 1998). The corrosion rate could be reduced by increasing AC frequency and current density (Uemura et al., 1994; Reznick, 1996; Wu et al., 1998). Wu et al. (1998) observed that when heating Pacific whiting stabilized mince at the current density of 2300 A/m² and at AC electrical frequencies of 5000 Hz and higher, the corrosion on the stainless-steel electrode surface essentially disappeared.

The effect of different AC frequencies and current densities on corrosion of electrodes indicated in Tables 11.3 (Zhao and Kolbe, 1999) and 11.4 (Samaranayake et al., 2005). Furthermore, Stancel and Zitny (2010) presented experiments with the direct Ohmic heating of milk and identified effects of the temperature of the flowing milk, flow rate, current density, and material of the electrode (electrodes were made from stainless steel, stainless steel with TiN coating and graphite). They confirmed that the effect of the electrode corrosion could be eliminated by using higher frequencies (about 10 kHz) from a pulsed power supply.

The effect of high AC frequency in minimizing undesired electrochemical reactions during Ohmic heating has been indicated in different works (Palaniappan et al., 1991; Uemura et al., 1994; Reznick, 1996; Amatore et al., 1998; Wu et al., 1998; Tzedakis et al., 1999; Assiry et al., 2003).

11.6 THE LOSS OF ENERGY AT THE ELECTRODE–FOOD INTERFACE

The ideal electrode in Ohmic heating of food should be corrosion resistant and have the ability to pass the total current to the food without any involvement in electrochemical reaction. However, it is difficult to get such an electrode. When voltage is applied to the system, the total current at electrode–food interface is the sum of capacitive and faradaic current (Tzedakis et al., 1999). The faradaic reaction is a heterogeneous charge-transfer reaction occurring at the surface of an electrode. Whereas capacitive current is the current flowing through an electrochemical cell that is charging/discharging the electrical double-layer capacitance. This current does not involve any chemical reactions (charge

TABLE 11.3

Effect of AC Frequency, Current Density on Degree of Corrosion of Stainless Steel in 2% Salt Solution

Electrode	AC Electrical Frequencies	Current Density Used	Solution Used/ Food Type	Effect on Electrode	Reference
Stainless steel	55,100, 200 Hz	>2300 A/m ²	2% salt solution	Corrosion covered the whole electrode	Compiled from Zhao and Kolbe (1999)
	500 and 1000 Hz	3500 A/m ²		Irregularly shaped corrosion spots	
	5000 Hz	3500 A/m ²		No visual electrode corrosion	

transfer), it only causes accumulation of electrical charges on the electrode and in the electrolyte solution near the electrode. This allows the generation of volumetric heat due to resistance developed in the food. However, due to the presence of the faradaic reaction, which results in partial electrolysis of the food components and corrosion of electrodes (Amatore et al., 1998), some amount of current is not used for the intended purpose. According to Tzedakis et al. (1999) the loss of energy in the form of a faradaic current is estimated between 20% and 40% of the capacitive current. Such a loss of energy can be minimized using pulsed Ohmic heating of high frequency and shorter pulse width, since they have a significant effect in minimizing electrochemical reactions at electrode–food interfaces as indicated in the above sections (Samaranayake and Sastry, 2005). In other words, in electrosynthesis processes, the Faradaic effect is the desired feature instead of Ohmic heating (Amatore et al., 1998) since the faradaic current is used for electrolysis of the solution.

TABLE 11.4

Effect of AC Frequency, Pulsed Width, and Duty Cycle on Corrosion Rate of Commonly Used Ohmic Heating Electrodes

Electrode	Major Elements Released during Corrosion	Parameters for Low Corrosion Rate			Remarks
		AC Frequency (kHz) (4 and 10)	Pulse Width (μs) (10–100)	Duty Cycle (%) (20–80)	
Stainless steel	Fe and Cr	10	10	20	Corrosion rates become enhanced at 4 kHz, compared with those at 10 kHz
Titanium	Ti	10	10	20	Corrosion enhanced at 10 kHz longer pulse widths, and at 4 kHz shorter pulse widths
		4	75	60	
Platinized-titanium	Pt	4	100	80	4 kHz yields greatly reduced corrosion rates with higher pulse widths and higher duty cycles
	Ti		50(75)(100)	40(60)(80)	
Graphite	C	10	10	30	Reduced corrosion rates at 10 kHz with shorter pulse widths

Source: Compiled from Samaranayake, C.P., Sastry, S.K., and Zhang, Q.H. 2005. Pulsed Ohmic heating—A novel technique for minimization of electrochemical reactions during processing. *Journal of Food Science* 70: E460–E465.

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12 Energy Efficiency and Control of the Ohmic Heating Process

Luc Fillaudeau and Sami Ghnimi

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12.1 INTRODUCTION

Owing to industrial and social requirements, but also to technical and scientific progress, the food processing industry is facing new challenges: a wide diversification of processing equipment and the emergence of new food matrices which are more and more complex. In the meantime, the choice of technologies and processes should achieve the following goals: (i) to ensure the microbiological security of a given product up to a date limit; (ii) to improve product quality through better control and understanding of the process and (iii) to enhance the competitiveness and reliability of the process.

Ohmic heating (direct Joule effect heating) is a reliable and efficient way to heat a wide range of products. Ohmic heating is defined as a purely volumetric and direct-resistance heating, in opposition to heating by conduction from a hot surface heat exchanger. The nonexistence of a hot wall should constitute a major advantage for food applications associated to high heating kinetics and homogeneity of treatment (interest for solid–liquid suspension), thereby avoiding the degradation of thermosensitive compounds through overheating (change in taste, undesirable reactions, burning) and reducing the fouling of the heat exchanger (constant thermal performances). However, the contribution of relative orientations of electric (\vec{E}) and velocity fields, (\vec{V}) (perpendicular, parallel orientation) or treatment in a laminar jet (no wall) constitute technical criteria that requires specific analysis. In food applications, the interactions between food and process need to be scrutinized. Thermal, electrical, and hydrodynamic performances constitute fundamental criteria to control the process even though Ohmic heating technologies may differ widely (Table 12.1).

TABLE 12.1**Technical Parameters and Constraints to Consider into Direct Joule Heater**

Ohmic Technology	Batch or Continuous Process
	Tubular, plane, or jet
	Electrode dimension and position (intrusive, affleurant)
	Electrode material (stainless steel, DSA)
Electric supply	Electric field: up to several 100 V/cm
	Frequency: 50 Hz to 30 kHz
	Current density: up to 5000 A/m ²
	Max power: up to 480 kW
Product	Homogenous liquid/solid–liquid suspension
	Fouling propensity

Within the past two decades, Ohmic heating has created intense industrial interest and new improved electrode materials and equipment designs have become available (Halden et al., 1990; Palaniappan and Sastry, 1991a,b; Sastry and Palaniappan, 1992; Fryer and Li, 1993; Imai et al., 1995; Roberts et al., 1998; Sastry and Salengke, 1998; Lima et al., 1999; Fillaudeau et al., 2001; Ayadi et al., 2004; De Halleux et al., 2005; Samaranyake et al., 2005a,b; Legrand et al., 2007). As reported in literature, different electro-heating methods, embraced by the food industry for processing a broad range of food products have several applications (HTST of solid–liquid mixture, sterilization of liquid food). The developments of new Ohmic sterilizers have reduced the cost by a factor of 10 between 1993 and 2003. Currently, at least 19 Ohmic heating operations have been supplied to customers in Europe, Asia, and the United States to produce a variety of high-quality products (heterogeneous foods such as fruits, meat mixtures, and tomato particles).

In this chapter, liquid food and solid–liquid suspension treatments with direct Joule effect technology are mentioned under energetic criteria (energetic efficiency, heating kinetics, and temperature homogeneity). The encountered difficulties and beneficial aspects (volume heating, fouling mechanisms, heterogeneous suspension treatment) are also reported. Conventional and alternative tools to ensure process security and to control an optimal heat treatment of food products are suggested.

12.2 ENERGETIC EFFICIENCY

12.2.1 POWER SUPPLY AND ELECTRODE MATERIAL

The passage of an electric current through a food heats by the Joule effect; the food behaves as a resistor in an electrical circuit. The advantages of continuous Ohmic heating are rapid heating with improved treatment homogeneity and high-energy efficiency. Although the technique appears both simple and advantageous, several difficulties are encountered in its application. It is already known that Ohmic heaters powered by low-frequency (50–60 Hz) alternating currents induce corrosion of stainless-steel electrodes and apparent electrolysis of the heating medium. These electrochemical phenomena can be effectively suppressed by using high-frequency alternating currents (Amatore et al., 1998; Wu et al., 1998; Samaranyake et al., 2005a). However, the use of high-frequency generators especially for industrial Ohmic heating may be limited by cost considerations. In addition, with high-frequency power supply the dielectric properties (electrical conductivity and relative permeability) of matrices should be investigated. Therefore, viable process control methods that up the energy efficiency are of great interest and primary, secondary, and thermal powers should be carefully considered. Ohmic heating focuses on thermal efficiency (η_p) in regards to input power issued from the secondary. Legrand (2005), Fillaudeau et al. (2006a), and Ghnimi (2008) demonstrated

that whatever the Ohmic device, the thermal efficiency (η_2) was close to 100% (superior du 90%) under standard working conditions.

$$h_1 = \frac{P_{\text{Second}}}{P_{\text{Prim}}} \quad \text{and} \quad h_2 = \frac{P_{\text{ther}}}{P_{\text{Second}}} \quad (12.1)$$

12.2.1.1 Low-Frequency Power Supply

Temperature regulation at the Ohmic heater outlet is carried out through the control of the electrical power (P_{max} generator, three-phase system, triangle or star connection). The power is controlled by a phase angle (voltage and current regulation, AC current, 50–60 Hz) up to the maximum acceptable voltage and intensity (U_{max} , I_{max}).

Electrolytic reactions may occur at the electrode–solution interface if continuous or alternating currents flow through an electrolyte. Electrolytic reactions can be prevented if the potential drop at the electrode–solution interface can be kept below the critical electrode potential, which depends on the physical and chemical properties of the electrode, pH values, current frequency, and density (Amatore et al., 1998; Sastry, 2003; Samaranayake and Sastry, 2005b). Electrolysis is unlikely because of the current frequency (50 Hz) and density ($<5000 \text{ A/m}^2$) used with a specific electrode material named DSA (dimension stable anode). DSA electrodes have been patented (Berthou et al., 1998) and are made out of titanium with a layer of noble metal oxides (Ru, Ir, Ta, etc.).

In this configuration, the input power (secondary) can hardly be equal to the maximal power (primary) because it directly depends on the electrical resistance between electrodes (electrical conductivity and shape of Ohmic cells). In Figure 12.1, the effective input power into Ohmic cells is reported versus electrical conductivity of flowing fluid for an Ohmic heater composed of three rectangular Ohmic cells in a series ($e = 15 \text{ mm}$, $w = 76 \text{ mm}$, and $L = 246 \text{ mm}$, electrical field perpendicular to the flow pattern, $\vec{E} \perp \vec{v}$) (Fillaudeau et al., 2004).

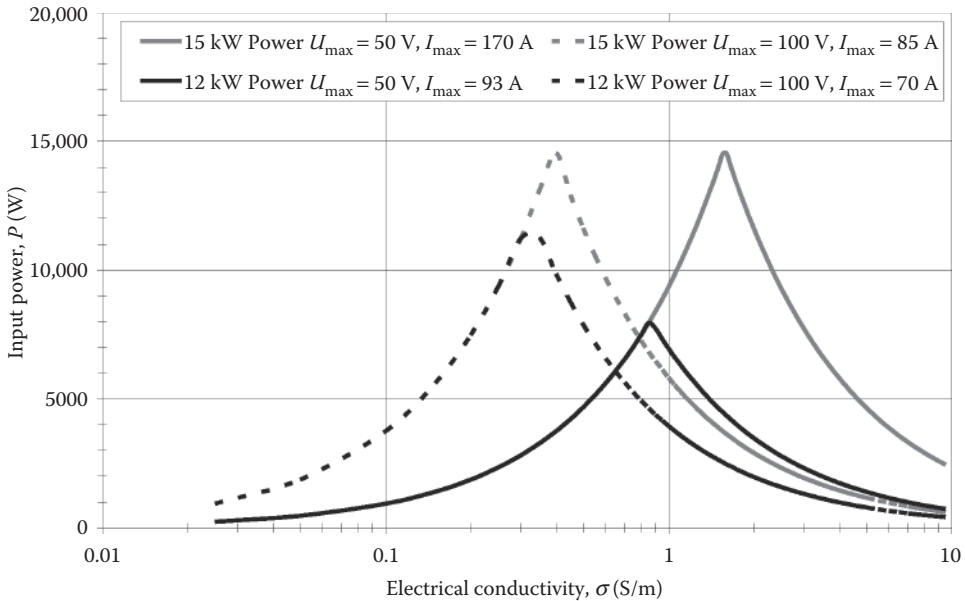


FIGURE 12.1 Input power (secondary) versus electrical conductivity in ERRO Ohmic heater (AlfaLaval-Vicarb, Fontanil-Cornillon, France) with 12 and 15 kW power supply (primary) and 50 and 100 V outputs (secondary).

12.2.1.2 High-Frequency Power Supply Systems

In this case, the power supply delivers bipolar potential pulses. Electrolysis is prevented by the use of high-frequency alternating voltage. Stainless-steel electrodes could be used instead of DSA material. The frequency is up to 30 kHz with adjustable voltage from 400 V up to 3800 V. Both positive and negative pulses of the bipolar pulse output have the same pulse width t_p (μ s), and are equally spaced by adjusting the delay time t_d (μ s) as illustrated in Figure 12.2:

$$\begin{aligned} T &= t_p + t_d \\ D &= \frac{t_p}{T} \end{aligned} \quad (12.2)$$

and

$$P_{\text{second}} = U_p \cdot I_p \cdot D \quad (12.3)$$

where t_s is the period of the signal (μ s), D is the duty cycle and, therefore, the power supplied to the Ohmic cell has the following form (Soojin et al., 2007; Ghnimi et al., 2007) where U_p is the peak voltage (V) and I_p is the peak current (A) delivered by the power supply. In our case, the maximum power supplied is equal to 50 kW. The power supplied to the Ohmic cell ($P_{\text{secondary}}$) was varied by adjusting the delay time between two adjacent pulses, whereas the pulse width was maintained constant and equal to 33 μ s. Ghnimi (2008) investigated the variations in energy efficiency of the power supply at different delay times. It appeared clear that the delay time has a significant effect on the energy efficiency of the power supply. When there is a small delay time (up to 10 μ s), the energy efficiency of the power supply is close to 90%. This efficiency can decrease up to 67% for delay times close to 110 μ s (Figure 12.3). For optimal control of the process, the duty cycle (D) could be used as a reference, better than delay time, for deduction of the energy efficiency of the power supply.

12.2.2 BULK TEMPERATURE PROFILE AND HOMOGENEITY

From a fundamental point of view, direct resistance heating of liquids is a complex physical problem where in a strong interaction of heat transfer, hydrodynamic and electric phenomena can be observed (Ould-El-Moctar et al., 1993). In an Ohmic heater, the equation of energy conservation integrates the viscous and electric dissipation. Coupling between the heat transfer and the hydrodynamic is through the nonlinear term and the viscous dissipation term whereas the coupling between electric and heat transfer is secured by the electric dissipation source term.

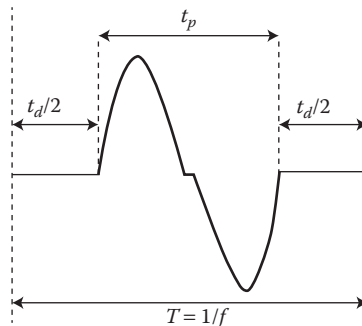


FIGURE 12.2 Schematic diagram of the centering of bipolar pulses.

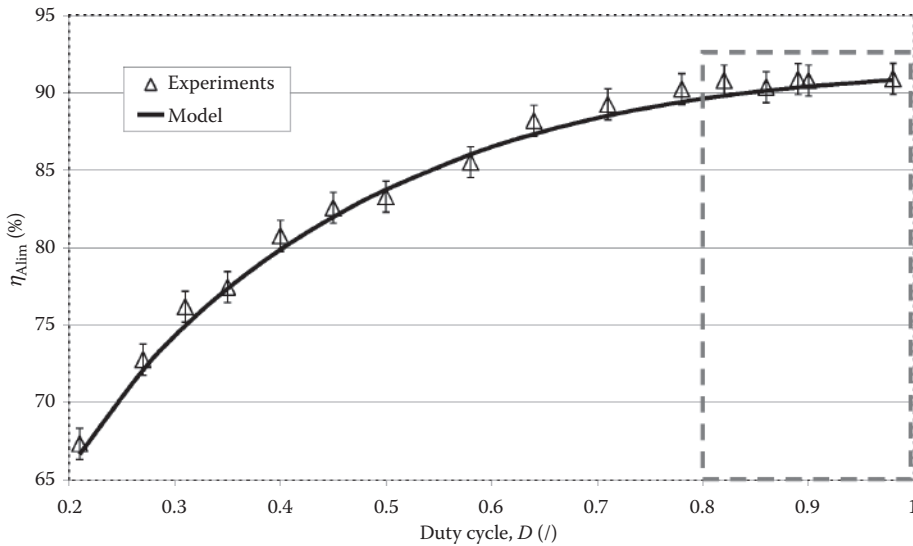


FIGURE 12.3 Energetic efficiency of the power supply versus the duty cycle—Jet cell. (From *Chemical Engineering Science*, 64, Ghnimi, S. et al., Axial temperature profile of Ohmically heated fluid jet: Analytical model and experimentation validation, 3188–3196, Copyright 2009, with permission from Elsevier.)

$$\mathbf{r} \cdot \mathbf{C} \cdot \frac{dT}{dt} = \nabla \cdot (\mathbf{1} \cdot \nabla T) + \mathbf{s} \cdot |\nabla U|^2 + \mathbf{F}_v \quad (12.4)$$

The equation of energy conservation (Equation 12.4) can be solved in all Ohmic systems (for batch and continuous, versus electric field orientation and jet cell) to determine an analytical expression (Table 12.2) of bulk temperature profile versus length and time. Some assumptions are necessary to solve the problems:

- Geometry of the channel is uniform (no singularity, no cross-section change).
- Working fluid is a homogeneous, Newtonian, incompressible ionic fluid for which the terms of electric force are negligible (equation of conservation of momentum).
- Thermophysical properties of the fluid (λ , C , ρ) remain constant with respect to temperature, except electrical conductivity (linear model: $\sigma = \sigma_0 \cdot (1 + m \cdot T)$).
- Velocity profile (plug flow model) is uniform along the apparatus (continuous process).
- Viscous dissipation is negligible compared to direct Joule effect (continuous process).
- Temperature profile at the channel entrance is uniform (continuous process).
- Thermal insulation condition is at the exit from the system as well as on all channel walls (adiabatic device).

Literature reports the analytical expression of bulk temperature profiles in Ohmic heaters (Table 12.2).

Thermal homogeneity in Ohmic heating has been extensively investigated with homogeneous fluid and solid–liquid suspension in batch and continuous processes. Experiments (Table 12.3) report local temperature measurements (insulated thermocouple, optical fiber, magnetic resonance imaging) or numerical simulations (home-made code, commercial FEM software) to get simultaneous flow solution, temperature, and electric fields. Literature reports that under specific flow and heating conditions, a strong divergence of temperature profiles across sections were observed and may be characterized by different wall temperatures at the bottom and the top of a section (Ould El

TABLE 12.2

Analytical Expression of Bulk Temperature Profile in Batch and Continuous Ohmic Heaters

Batch Fryer et al. (1993)	$T(t) = \frac{1}{m} \cdot \left[(1 + m \cdot T_e) \cdot \text{Exp} \left(\frac{m \cdot s_0 \cdot E^2}{r \cdot C} \cdot t \right) - 1 \right]$
$\vec{E} // \vec{V}$: Benabderrahmane and Pain (2000)	$T(x) = \frac{1}{m} \cdot \left[\left(1 + 2 \cdot m \cdot \left(\frac{m}{2} \cdot T_e^2 + T_e + \left(\frac{J^2 \cdot SP}{Q \cdot r \cdot C \cdot s_0} \right) \cdot x \right) \right)^{1/2} - 1 \right]$
$\vec{E} \perp \vec{V}$: Fillaudeau et al. (2004)	$T(x) = \frac{1}{m} \cdot \left[(1 + m \cdot T_e) \cdot \text{Exp} \left(\frac{m \cdot s_0 \cdot SP \cdot E^2}{Q \cdot r \cdot C} \cdot x \right) - 1 \right]$
$\vec{E} // \vec{V}$ in a jet: Ghnimi et al. (2009)	$T(x) = \frac{1}{m} \cdot \left[\left(1 + 2 \cdot m \cdot \left(\frac{m \cdot T_e^2}{2} + T_e + \left(\frac{I^2 \cdot v_{\text{nozzle}}}{3 \cdot r \cdot g \cdot p^2 \cdot R_{\text{nozzle}} \cdot s_0 \cdot C} \right) \cdot x \right) \right)^{1/2} - 1 \right]$

Moctar et al., 1993; El Hajal et al., 1998). In fact, the thermo-physical properties of the liquid in flow are dependent on temperature, and the temperature field, in its turn, depends on the residence time. Natural convection can occur and generate additional movement to the main flow and can imply a mixed convection regime in continuous mode or natural convection in batch mode. This phenomenon is strengthened with heterogeneous product such as solid–liquid suspension.

TABLE 12.3

Experimental and Analytical Investigation of Temperature Profile during Batch or Continuous Ohmic Heating of Homogeneous Liquid and Solid–Liquid Suspension

Process	Homogeneous Liquid	Solid–Liquid Suspension
Batch	Analytical expression of bulk temperature Numerical simulation: Local measurements (ThC, fiber optique): Li et al. (2004), Marcotte and Piette (1998),	Differential equations (coupling between electric and heat transfer) Numerical simulation: Sastry and Palaniappan (1992), Sastry and Salengke (1998), Fu and Hsieh (1999), Davies et al. (1999), Ye et al. (2004), Marra et al. (2009). Measures locales (ThC, fiber optique): Zareifard et al. (2003), Zhong and Lima (2003), Ozkan et al. (2004), Sensoy and Sastry (2004). Measures globales (MRI), Ye et al. (2003, 2004).
Continuous	Differential equations (coupling between hydrodynamic, electric and heat transfer) and analytical expression of bulk temperature. Numerical simulation: de Alwis and Fryer (1992), Benabderrahmane and Pain (2000). Experiments with liquid food: (Ayadi, 2005), Fillaudeau et al. (2001, 2004, 2006a), Ghnimi et al. (2009), Bansal and Chen (2006).	Differential equations: (coupling between hydrodynamic, electric and heat transfer) Numerical simulation: Ould-El-Moctar (1992), Quarini, (1995), El-Hajal (1997), Ivory (2000), Marcotte et al. (2004), Leizerson and Shimoni (2004). Experiments with food matrices: Yang et al. (1997), Eliot-Godereaux et al. (2001), Legrand (2005).

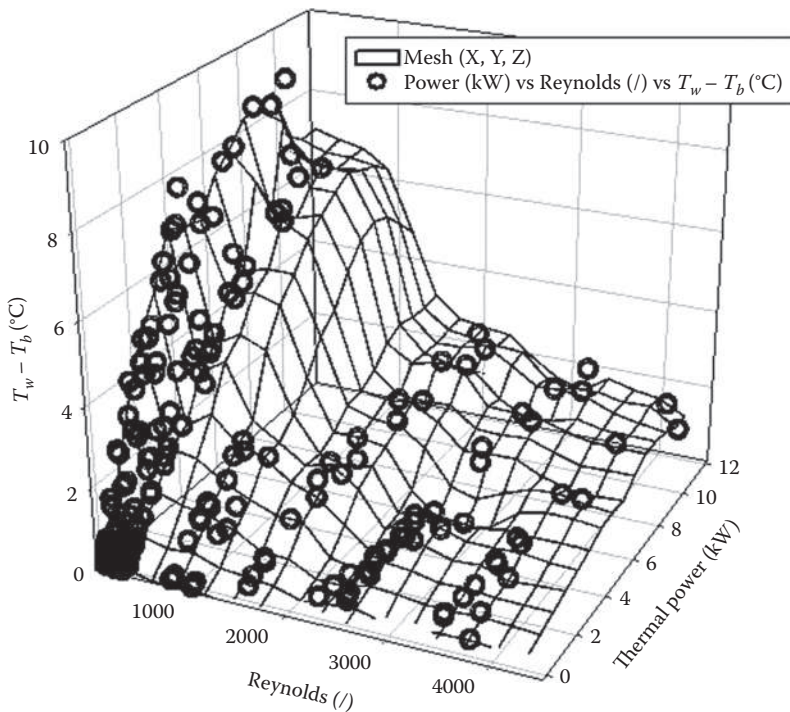


FIGURE 12.4 Temperature difference ($T_w - T_b$) versus heat power and flow regime (ERRO Ohmic heater from AlfaLaval-Vicarb, Fontanil-Cornillon, France). (From Fillaudeau, L. 2004. Chauffage des fluides agroalimentaires par effet Joule direct: conductivité électrique et expressions analytiques des profils de température. *J. Ind. Agr. Alim.*, Juin 2004, pp. 10–19.)

The temperature gradient between wall and bulk, $T_w - T_b$, should remain as shallow as possible for the successful treatment of fouling liquid food. The main goal is to reach a temperature difference equal or lower than those commonly generated with a tubular or plate heat exchanger. Consequently the quantification and modelling of the temperature gradient appears essential. In Figure 12.4, the evolution of the temperature gradient, $T_w - T_b$ is reported.

12.2.3 FOULING

Fouling stands as a complex and misunderstood phenomena in most of the food industries. Continuous or batch processes are carried out in the food industry and fouling occurs in the equipment with a widespread of kinetics (from minutes up to years) and propensities (from micrometers up to centimeters). The control and understanding of fouling phenomena is of industrial interest as it may be related to: reduction of process performances, energetic consumption, and water management. Monitoring fouling during Ohmic heating and the consequent cleaning processes can provide useful information for operational decision makers in food product plants, but is also required for security reasons and for the safety of the consumer. In Figure 12.5, a propensity to fouling is observed during UHT of whole milk in agreement with the operating condition.

In an Ohmic heater, overheating of poor conducting liquids adjacent to hot surfaces not only causes burning or degradation of the liquids, but also leads to heat exchanger fouling. The local temperature in a direct Joule effect heater is then fundamental and can be determined either by physical measurement (i.e., magnetic resonance imaging, Ye et al., 2003) or by numerical simulation using a control volume code (Ould El Moctar et al., 1993).

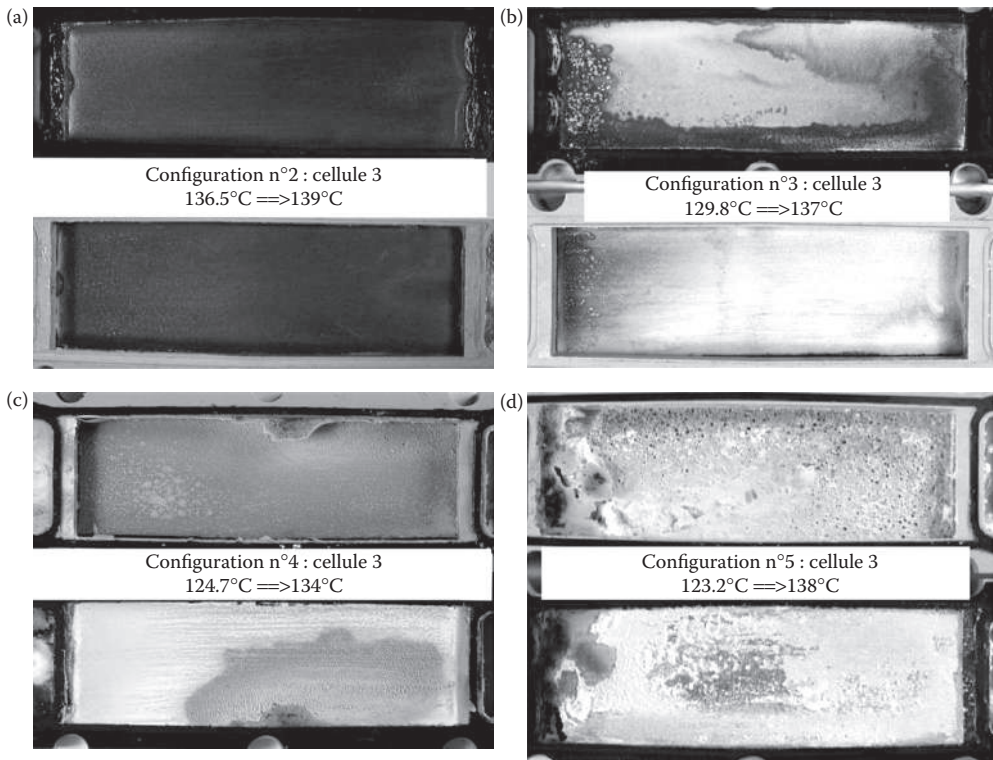


FIGURE 12.5 Fouling generated by whole milk in ERRO Ohmic heater (Alfa-Laval-Vicarb, Fontanil-Cornillon, France)—Observation of 3rd cell: (a) (335 min, 298 l/h), (b) (277 min, 272 l/h), (c) (710 min, 273 l/h), and (d) (195 min, 178 l/h).

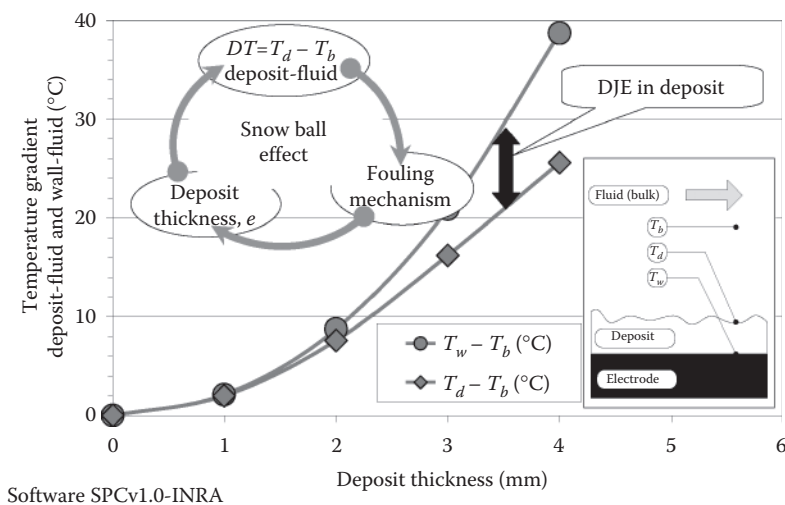


FIGURE 12.6 Evolution of the mean temperature differences, $T_b - T_w$ and $T_b - T_d$ along Ohmic heater versus the deposit thickness (Fluid: whole milk, $Q = 200 \text{ l} \cdot \text{h}^{-1}$, $T_{be} = 50^\circ\text{C}$, $T_{bs} = 92^\circ\text{C}$). (From Fillaudeau, L. et al., 2006a. *Journal of Dairy Science*, 89, 4475–4489. With permission.)

The temperature profiles of fluid, T_b , deposit, T_d and electrode surface, T_w versus heat exchanger length with an increasing deposit thickness can be simulated as reported in Figure 12.6. For an element dx , the generated Joule inside the deposit is proportional to its thickness: heat generated in this layer should be transferred to the fluid by convection. The thermal balance between the fluid, the deposit, and the electrode results from the physical (ρ , C , λ , μ) and electrical (σ) properties of the fluid and the deposit. In addition, the flow conditions at the deposit–fluid interface define the magnitude of the heat convection coefficient. The mean temperature gradients between the electrode surface and bulk milk, $T_w - T_b$ and between deposit surface and bulk milk, $T_d - T_b$, plotted for an Ohmic heater versus the deposit thickness exhibit exponential shape. The Joule effect inside the deposit causes overheating of the wall that would make fouling spiral out of control, as the fouling mechanism undergoes the “Snowball effect”. This phenomenon appears to be specific to the Ohmic heater (direct Joule effect and $\vec{E} \perp \vec{V}$) and is related to a strong interaction between the Joule effect inside the deposit and the convective transfer at its surface.

Delplace (1995) reported that the denaturation kinetics of whey protein (dairy product) were temperature dependent and demonstrated that in PHE. Denatured protein in the thermal boundary layer was involved in deposit formation with a contribution of local hydrodynamics. In a realistic configuration with an Ohmic heater, if a velocity difference between the fluid flowing in the core and the fluid flowing close to the electrode (boundary layer) does exist, then the temperature gradient in clean conditions (without fouling) can generate a driving force to initiate fouling. Numerical simulation consolidates the experimental results obtained during heat treatment of whole milk showing that instability of thermal and electrical parameters is systematically created by the fouling at electrode surfaces due to an increase of deposit and wall temperatures.

12.3 CONTROL OF THE OHMIC HEATING PROCESS

12.3.1 BULK AND ELECTRODE TEMPERATURES CONTROL

A major challenge in evaluating Ohmic heating systems is monitoring product temperature and critical area (electrode surface) during the heating process. Temperature measurement is fundamental and should satisfy several challenges in relation with security of the process and safety of the consumer.

At laboratory scale, different temperature mapping systems have been investigated such as optical fiber, magnetic resonance imaging, and time–temperature integrator. In pilot plant or industrial scales, the temperature probe must be designed appropriately to permit a rapid response time while being relatively rugged to withstand repeated use. It must have an appropriate internal insulation to eliminate the risk of electrical interference and to protect the logging unit. Finally, in order to get a complete indication of the temperature distribution within a product, probes containing multiple measurements are required.

In Ohmic heating, the presence of an electrical field makes measurements of fluid and electrode surface temperature a delicate matter, since the sensor may be the seat of electrical energy dissipation by the Joule effect, thereby completely falsifying the measurement results. In addition, an intrusive sensor must not disturb the flow, since local temperature rise depends on the residence time in the cell and the presence of a recirculation zone or dead zone, even a reduced one, due to the presence of the sensor may lead to erroneous measurements. While new temperature measuring systems have been developed, thermocouples still offer reliable and low cost means of monitoring temperature. However, the use of thermocouple probes in an Ohmic heating environment can lead to problems such as electrical discharges and signal perturbations inside the heating device. The ideal measuring device should be as small as possible, fully insulated and safe. It should not be susceptible to electrical interference while being robust and exhibiting a fast response time.

Taking into account these constraints, different solutions have been proposed to control temperature within the electric field. Fillaudeau et al. (2004 and 2006a) and Ayadi et al. (2004) measured

the electrode wall temperatures by using thermocouples (Corame sensor, type J thermocouple electrically insulated, ref: J05X, accuracy $\pm 0.5^\circ\text{C}$, Corame, C2M, Mont Saint Aignan, France). These thermocouples were implanted on the outer side of plane electrode. Zell et al. (2009) compared different rapid response thermocouple probes (mineral insulated single and multipoint probes, thermocouple in glass-lined tubing and in stainless-steel sheath) for Ohmic heating applications. Legrand (2005) used T-Type thermocouples coated with Teflon ($D = 1\text{ mm}$, $L = 150\text{ mm}$) to measure temperature within a solid–liquid suspension.

12.3.2 ONLINE FOULING MONITORING

Fouling is usually not visible from outside the industrial processing equipment, and thus can only be ascertained from its effects, such as by measuring heat transfers (Bott, 1995; Lalande et al., 1989) or pressure drops (Burton, 1968; Delplace, 1995), which in the case of small, local deposits may not be significant enough to allow an operational decision to be made. Other sophisticated methods have been developed to monitor fouling such as silicon sensors (Stenberg et al., 1988), micro-strip monitoring technique (Root and Kaufman, 1992), photo-thermal deflection method (Fujimori et al., 1987), optical techniques (Withers, 1996), ultrasonic method (Withers, 1996; Pereira et al., 2006) or flux-meters (Davies et al., 1997). Unfortunately, most of them (i) require important instrumentation, (ii) are not always adapted to non-transparent equipment, (iii) are not compatible with an industrial environment since they are often restricted to laboratory use, and (iv) are not adapted to cleaning requirements encountered in the food industry (Janknecht and Melo, 2003).

In continuous Ohmic heaters (tubular, plate, or jet), conventional fouling measurements (pressure drop, heat transfer, or global electrical parameters) could not be used. First, the variation of pressure drops with time is not significant. The constant value of the pressure drop in the Ohmic heater may be explained by the large cross-section and small flowing length in comparison to conventional tubular or plate heat exchangers. In addition, deposits may be located at electrode surfaces and pressure drop measurements are inappropriate in a fluid jet. Second, energy efficiency is remarkable, remaining higher than 90% in major cases. The heat dissipation coefficient, Rh_{CO} with a value close to 1 shows that there was no significant deviation of electrical consumption (secondary) in spite of the existence of a layer of deposit at the surface of the electrode. If Rh_{CO} collapses, it demonstrates a rapid and irreversible fall of the thermal and electrical parameter linked to fouling intensity and thermal degradation at the electrode surface (Figure 12.5d).

An innovative fouling sensor based on local thermal performances has been validated to monitor fouling propensity within Ohmic heaters (cell jet). The thermal sensor was made of a platinum resistance and two thermocouples (type K). The platinum probe acted as a hot-wire sensor. A ceramic sheath ensured electrical insulation between the stainless steel and platinum hot wire. The first thermocouple was welded half way along the platinum probe and measured the wall temperature at the sensor-product or deposit interface. The second thermocouple measured the bulk temperature (Figure 12.7). The platinum wire was connected to a direct current generator (0–50 mA). The electric current (I) and potential (U) applied to the standard resistance were recorded and the heat power (P , 0–250 mW), the heat flux (ϕ , 0–300 W/m²), and the electric resistance (R) were calculated. Each sensor signal (I , U , T_w , and T_b) was converted and recorded on a computer with specific acquisition software.

Under clean conditions, a moderate heat flux (0–300 W/m²) and permanent flow regime is applied. In these conditions, a thermally and hydrodynamically developing flow around the sensor is assumed; then the local heat-transfer coefficient, h , reaches an important value ($>1000\text{ W m}^{-2}\text{ K}^{-1}$). It induces that the temperature difference between wall and bulk tends toward 0⁺ (in agreement with the precision of thermocouples). An overview of the heat transfer in the probe and the product leads to a calculation of thermal resistance of the deposit or thickness, if its thermal conductivity is known (Fillaudeau, 2006b).

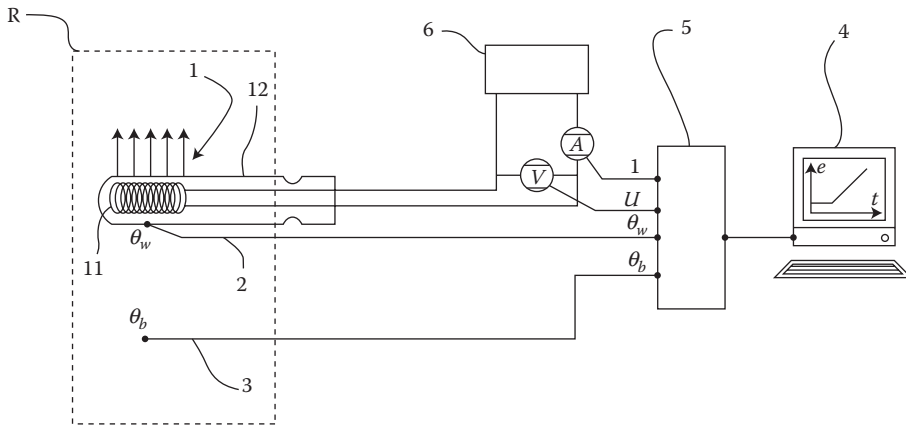


FIGURE 12.7 Principle of fouling sensor (INRA patent n°FR2885694).

Flux and power were determined with geometrical dimension and electrical parameters (I , U). Heat transfer may be formulated for a constant flux and in a system in which a deposit layer may exist. The temperature difference between wall and bulk, DT , is easily formulated (Equation 12.5):

$$DT = T_w - T_b = \frac{P}{2 \cdot p \cdot L} \cdot \left(\frac{1}{h \cdot (r + e_f)} + \frac{\text{Ln}(1 + e_f/r)}{1_f} \right) \quad (12.5)$$

Ghnimi (2008) validated this fouling sensor as an accurate method of online monitoring of fouling and cleaning phenomena during continuous Ohmic heating (whey proteins and chicken blood product) by using fluid jets. The sensor was located at the outlet of the Ohmic heater. In Figure 12.8, fouling/cleaning monitoring of whey protein deposit in the Ohmic heater is reported. This experimental investigation highlights that the fouling is essentially located in the electrode of mass. The fouling real-time diagnosis demonstrated that the deposit thickness remains negligible after 4 h of test runs and does not impact the thermal or electrical performances of the Ohmic cell.

12.3.3 HEAT DISSIPATION COEFFICIENT, Rh_{CO}

The definition of the heat dissipation coefficient in the Ohmic heater, Rh_{CO} is based on the following assumption: “The contact between a fluid (food product) and a surface (electrode) implies the occurrence of interactions. These interactions may induce a deposit on the surface whose growth kinetics may be driven by a temperature difference or chemical reactions due to temperature. If the deposition occurs then the thermal and electrical properties of the deposit will have consequences on heat transfer mechanism, as well as on process performance.”

Ohmic heating presents several advantages but for efficient implementation in the food industry, different factors such as fouling propensity and electrical conductivity of deposits have to be considered and accurately quantified. When fouling occurs, an additional electrical resistance can be created at the surface of the electrodes, resulting in a new electrical system. This layer is motionless and the Joule effect occurs there, just as it does in the flowing product. In any case, the electrical resistance of the layer will determine the performance of the system. In this new formulation Equation 12.6, the first term corresponds to heat generated in the deposit and the second to that in the flowing product.

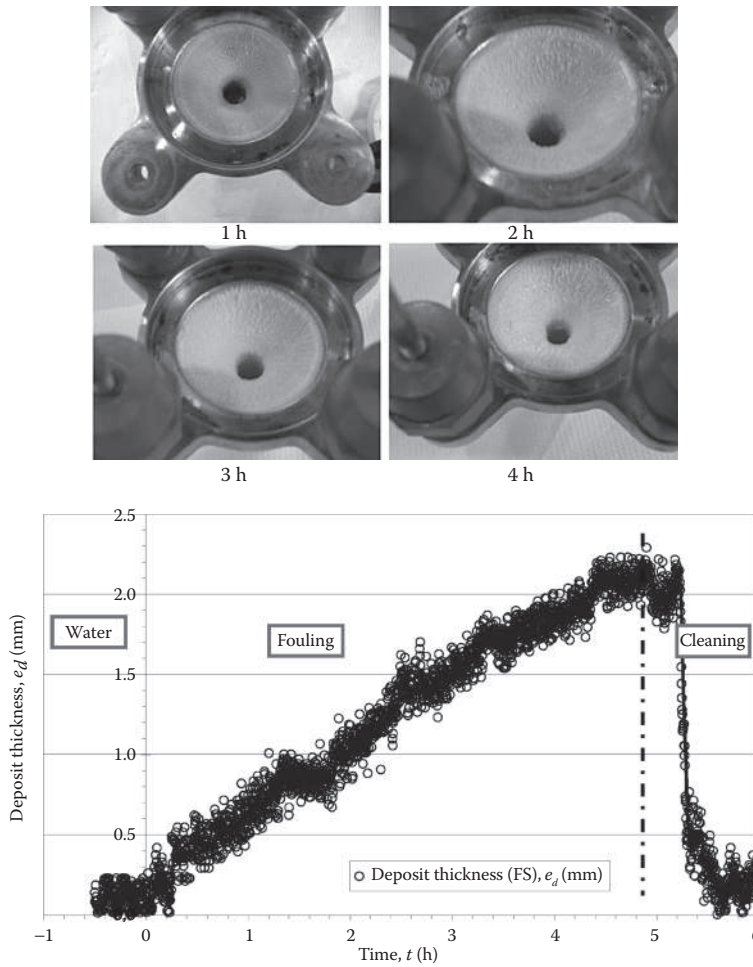


FIGURE 12.8 Online fouling and cleaning monitoring by hot-wire method at the outlet of a continuous Ohmic heater—Observation of mass electrode (jet Ohmic heater, model dairy product, $Q = 206$ l/h, $T_{inlet} = 62^\circ\text{C}$, $T_{outlet} = 91^\circ\text{C}$). (From *Chemical Engineering Science*, 64, Ghnimi, S. et al., Axial temperature profile of Ohmically heated fluid jet: Analytical model and experimentation validation, 3188–3196, Copyright 2009, with permission from Elsevier.)

$$P_{\text{second}} = I^2 \cdot (R_f + R) = I^2 \cdot \left(\frac{1}{s_f} \cdot \frac{e_f}{S} + \frac{1}{s} \cdot \frac{e - e_f}{S} \right) \quad (12.6)$$

Heat generated in this layer may be transferred to the fluid through heat convection or it can induce reactions inside the deposit by temperature increase. The balance will be a complex equilibrium between the properties of the layer (electrical and thermal conductivity, temperature sensitivity) and heat-transfer coefficient depending on the hydraulic conditions.

An increase of electrical resistance from the fouling induces a potential drop. The fluid is also less heated implying an increase in the global voltage required to maintain performance levels. If the deposit constitutes an electrical resistance, the electrical consumption should be increased to deliver the same thermal power. To follow the fouling effect in the Ohmic heater, a criterion: the heat dissipation coefficient, Rh_{CO} (Equation 12.7) based on electric (I , U) and thermal (Q , ρ , C , T_2 , T_3) powers

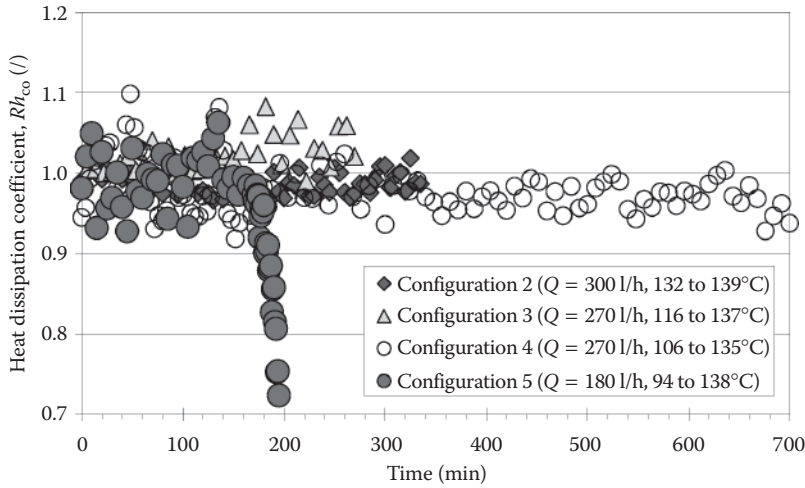


FIGURE 12.9 Heat dissipation coefficient, Rh_{CO} versus time and thermal power in Ohmic heater (configurations 2–5). Fouling generated by whole milk in ERRO Ohmic heater (Alfa-Laval-Vicarb, Fontanil-Cornillon, France). (From Fillaudeau, L. et al., 2006a. *Journal of Dairy Science*, 89, 4475–4489. With permission.)

is defined. This ratio is considered under clean conditions ($t = 0$) and versus time (t). If a deviation of the heat dissipation coefficient, Rh_{CO} , is observed, it means that fouling induces additional energy dissipation.

$$Rh_{CO} = \frac{(P_{\text{second}}/P_{\text{ther}})_{t=0}}{(P_{\text{second}}/P_{\text{ther}})_t} \quad (12.7)$$

During the sterilization of whole milk, Fillaudeau et al. (2006) observed that the deposit formed inside the Ohmic heater appeared similar to classical type A and B fouling in PHE, although chemical analysis could not be performed. The Ohmic heater performance remained constant even with a deposit whereas in PHE, the heat-transfer coefficient decreased and the pressure drop became greater. However, a physical threshold is reached when the heat generated inside the deposit can no longer be evacuated, then a drift of electrical and thermal parameters is observed (Rh_{CO} collapse) which indicates a thermal degradation of the deposit (burning due to Joule effect) as reported in Figure 12.9.

NOMENCLATURE

LATIN LETTERS

C	specific heat capacity ($\text{J kg}^{-1} \text{K}^{-1}$)
D	duty cycle (dimensionless)
DP	pressure drop (bar)
e	thickness (m)
E	electrical field (V m^{-1})
f	frequency (1/s)
h	convective heat-transfer coefficient ($\text{W K}^{-1} \text{m}^{-2}$)
I	current (A)
J	current density (A m^{-2})
L	length (m)
m	temperature factor ($^{\circ}\text{C}^{-1}$)

P	power (W)
Q	volume flow rate ($\text{m}^3 \text{s}^{-1}$)
r	radius (m)
R	electrical resistance (Ω)
Re	Reynolds number (dimensionless)
Rh_{CO}	heat dissipation coefficient (dimensionless)
S	surface area (electrode) (m^2)
SP	section (m^2)
t	time (s)
T	temperature ($^{\circ}\text{C}$)
U	electrical potential (V)
v	velocity (ms^{-1})

GREEK LETTERS

μ	viscosity (Pa s)
λ	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
ρ	volume mass (kg m^{-3})
σ	electrical conductivity (S m^{-1})
η	energy efficiency (%)
Φ_v	viscous dissipation (W m^{-3})
∇	gradient
$\nabla \cdot$	divergent

SUBSCRIPT

b	product (bulk)
d	delay
e	inlet
f	fouling
p	pulse
prim	primary (electrical)
second	secondary (electrical)
s	outlet
ther	thermal
w	wall

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Section 5

Equipment for Ohmic Heating

13 Ohmic Heating Laboratory Units

Sanjay S. Sarang, Brian F. Heskitt, and Sudhir K. Sastry

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13.1 INTRODUCTION

Ohmic heating occurs when alternating current is passed through material that is in contact with the electrodes. Ohmic heating can be applied for thawing frozen foods, blanching, extraction, fermentation, and pasteurization. It has been receiving considerable attention in recent years for aseptic processing of multicomponent systems. This is mainly due to its ability to heat materials uniformly and rapidly, leading to a less aggressive thermal treatment. Clearly a knowledge base needs to be developed before Ohmic heating can be commercially used for the above-mentioned applications. This chapter is intended to enable the beginner to understand the basic design of various lab scale Ohmic heaters and the units that make up an Ohmic heating setup.

At the outset, it should be recognized that a vast variety of Ohmic heaters exists, including some that have not yet been realized. The only limit, aside from the laws of physics and operator safety, is the designer's creativity. However, we focus here on specific designs developed in the Ohmic heating laboratory at The Ohio State University. The design types and dimensions discussed are specific to these laboratory applications. However, they are presented here with the hope that those beginning a research program in Ohmic heating may benefit from them.

A schematic of a laboratory scale Ohmic heating setup is shown in Figure 13.1. A typical power source is low-frequency (50–60 Hz) AC power coming from a public utility supply. The internal energy generation rate in Ohmically heated material is a product of electrical conductivity of the material and the square of the voltage gradient across it. In other words, the heating rate of the material depends on the electric field strength or the power input. Voltage, or the power input to the Ohmic heaters, can be controlled by using a variable transformer. Use of an isolation transformer can greatly reduce potential shock hazards for the operator. Voltage and current transducers are used to measure the voltage across the sample material and the current flowing through it, respectively. Thermocouples are used to measure temperature; however, a key consideration is electrical interference due to the passage of current through the thermocouple wires. The obvious remedy, Teflon-coated thermocouple junctions, may be used but tend to slow thermocouple response; a critical difficulty when heating is rapid. A preferable solution is signal isolation, whereby current from the power source does not interfere with the thermocouple signal, enabling even bare thermocouple wires to transmit signals without interference. Signals from the thermocouples and the voltage and current transducers can be fed to a data logger and values recorded.

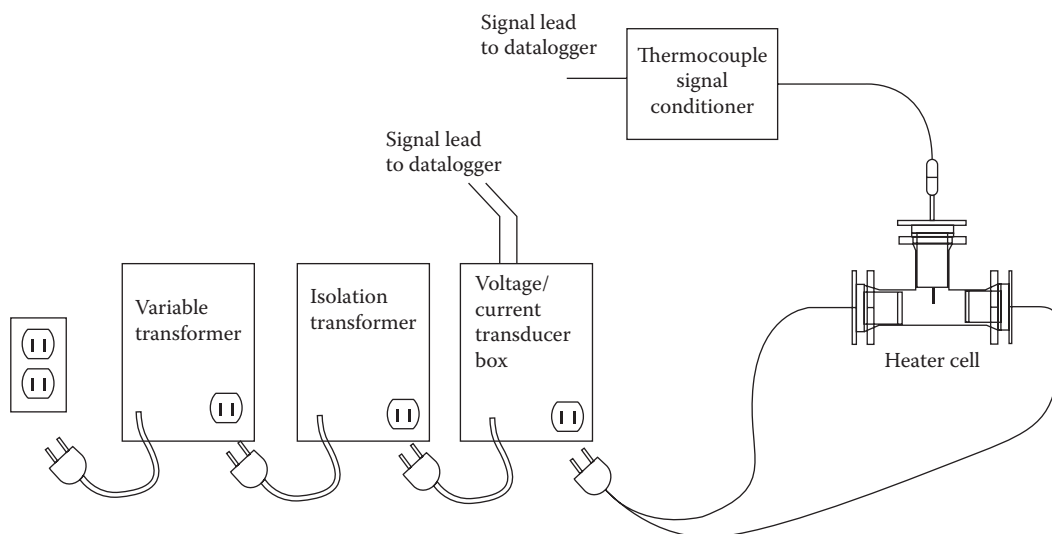


FIGURE 13.1 Basic components making up an Ohmic heating setup.

For obtaining a pulsed Ohmic heating power supply or for frequencies other than 50 or 60 Hz, electrodes can be connected to an IGBT power supply. IGBT typically operates at high frequencies (up to 20 kHz). Outputs from the power supply and the frequency generator in the IGBT power supply should be connected to a digital oscilloscope to monitor the applied and actual pulse width and frequency.

“Electrodes in Ohmic heating can be regarded as a ‘junction’ between a solid-state conductor (i.e. current feeder) and a liquid-state conductor (i.e. heating medium)” (Samaranayake and Sastry, 2005, p. 125). Materials such as aluminum, stainless steel, rhodium-plated stainless steel, carbon (graphite), glassy carbon, platinum, titanium, and platinized titanium have been studied and used as electrodes for Ohmic heating applications. Food materials can be considered as a complex mixture of several different chemical compounds and various undesirable electrochemical reactions can potentially occur during Ohmic treatment, unless precautions are taken either with the electrode material or the frequency of operation (see Chapter 9 for a more detailed discussion). Samaranayake and Sastry (2005) studied electrochemical behavior of four different electrode materials under Ohmic heating conditions and found stainless steel to be the most electrochemically active and platinized-titanium to be relatively inert. Care is needed in selection of electrode material and operating frequency.

Ohmic heaters for laboratory use can be classified according to their application.

13.2 ELECTRICAL CONDUCTIVITY MEASUREMENT SETUPS

An Ohmic heating device for electrical conductivity measurement can be a glass, polycarbonate or Teflon cylinder with (possibly) 1 in. internal diameter (Wang and Sastry, 1997a,b; Lima et al., 1999; Castro et al., 2003 and 2004; Zareifard et al., 2003; Kulshrestha and Sastry, 2006). Palaniappan and Sastry (1991a,b), a steel tube with a Teflon sleeve inside it, for electrical insulation and inertness, to make a cylindrical sample chamber. The steel tube device is the first-generation device, and is not currently the recommended option. The ends of the cylinder are fitted with electrodes and secured using plastic spacers. The distance between the electrodes can be varied. The electrode seals are maintained with o-rings. The sample of which electrical conductivity is to be measured is placed between the electrodes, taking care to ensure that the sample is in contact with electrodes at all times. There may be one or more ports on the top for locating thermocouples or pouring liquid

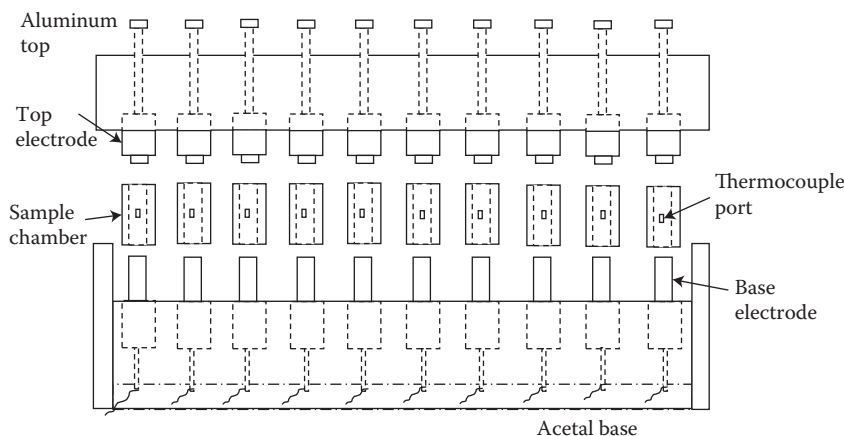


FIGURE 13.2 Schematic view of a multi-chamber Ohmic heating device, which enables the determination of electrical conductivity of small food particles.

materials. The holes can be equipped with pressurized fittings for type-T thermocouples for monitoring temperatures. These are basically static Ohmic heating cell units; however, the cells can be mounted on a shaker to ensure mixing of the material (Wang and Sastry, 1997a). The heaters can be jacketed for maintaining temperature inside the cell (Palaniappan and Sastry, 1991a,b; Castro et al., 2004). These heaters can also be pressurized and electrical conductivity measurements done at elevated temperatures.

The process of electrical conductivity measurement, using the single cell Ohmic heater described above, can become very time consuming especially if the electrical conductivity of multiple samples is to be determined. An Ohmic heating device wherein electrical conductivity of 10 samples could be determined at a time, was developed by Tulsiyan et al. (2008) and used for determining electrical conductivity of various food samples (Tulsiyan et al., 2008; Sarang et al., 2008). This device consisted of a base made from acetal and a top made from aluminum, which housed 10 electrodes (see Figure 13.2). Ten Ohmic heating cells were constructed from Ultem®. Food samples could be heated by placing them in the cells and sandwiching them between the electrodes. Thermocouples with compression fittings were used and temperature at the center of each sample was measured. Cells were made sufficiently strong, and sealed, so that they could be heated to sterilization temperatures. A bank of relays was used which directed the order in which the cells were heated. This setup also had the advantage of being small enough to accommodate appropriately cut and cored cylindrical food particles; this is generally not possible with heaters that are larger. Electrical conductivities of a number of individual vegetable pieces have been determined in this manner.

13.3 BATCH HEATERS

The rectangular-trough heater can be the simplest form of lab-scale Ohmic heater. An Ohmic heating box made of a transparent Plexiglas® block was used by Wang et al. (2007). This box was covered with foam boards to minimize heat and evaporation losses to the surroundings, and mounted on the magnetic stirrer. The material can be heated by supplying power to the rectangular flat electrodes placed at the ends of the rectangular container (Gupta, 2005).

Another kind of batch Ohmic heater is a glass T-tube with a 2-in. internal diameter (see Figure 13.1) for heating products (Sensoy and Sastry, 2004; Salengke and Sastry 2007; Sarang et al., 2007). A pair of electrodes is again fixed at both ends using plastic spacers. The top can be designed so

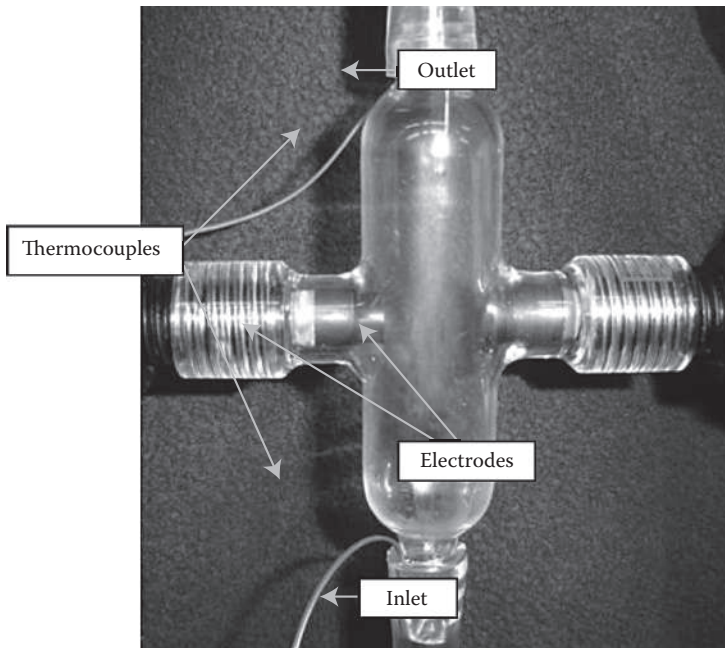


FIGURE 13.3 Continuous Ohmic heater.

that multiple thermocouple probes could be inserted. Also, the cell can be pressurized so that the product can be heated to sterilization temperatures (Sarang et al., 2007).

13.4 CONTINUOUS HEATER

A laboratory scale continuous Ohmic heater can be a glass tube with four openings as shown in Figure 13.3. A pair of cylindrical electrodes is fixed at two ends with the plastic spacers. The other two ends are connected to plastic or other nonconductive tubing. A simple pump can be used to continuously pump the material to be heated through the Ohmic heater. The temperature at the inlet and the outlet of the Ohmic heater can be monitored.

13.5 REACTOR VESSELS

An experimental fermentor for studying the metabolic activity and growth kinetics of selected lactic acid bacteria under Ohmic heating conditions was used by Cho et al. (1996, 1999) and Loghavi et al. (2007). The fermentor is a glass vessel with a water jacket, as shown in Figure 13.4, or with a water circulation coil attached to a water bath, to maintain the temperature of the medium. The lid will have openings for the electrodes, thermocouples, inoculation, pH probe tube, and fraction collector tube. The medium can be continuously agitated using a magnetic stirrer. Sample streams can be sent through a flow-through pH probe for monitoring pH changes in the fermentor, and at regular intervals fermentation samples can be collected in a fraction collector.

The batch Ohmic heating reaction vessel, shown in Figure 13.5, was used by Assiry et al. (2003, 2006) to determine the degradation kinetics of ascorbic acid during Ohmic heating. Samaranayake and Sastry (2005) used the same reaction vessel to study electrochemical reactions during Ohmic heating. The electrodes were rectangular (7.5 cm \times 5.2 cm) with a radius of curvature of \sim 4.5 cm. The vessel is jacketed to circulate heating or cooling fluid and perform the experiments at controlled temperatures.

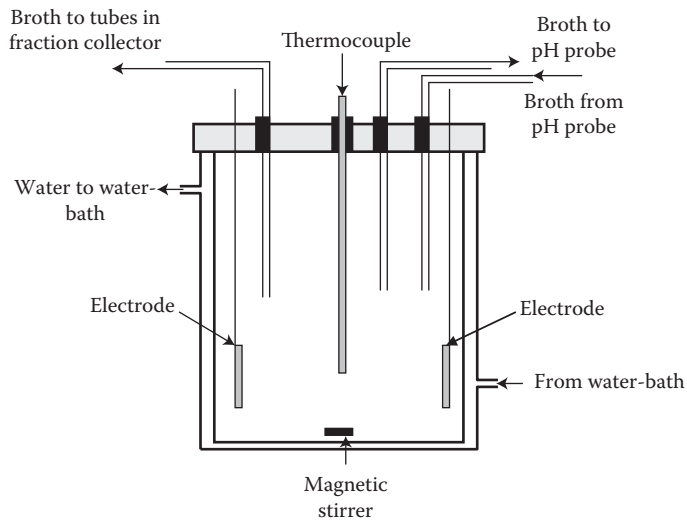


FIGURE 13.4 Schematic diagram of fermentation vessel.

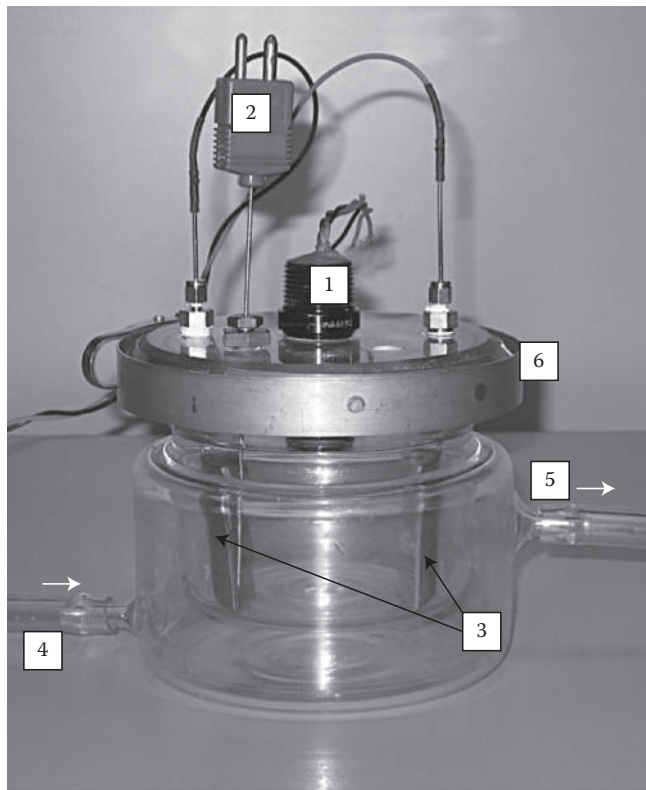


FIGURE 13.5 Laboratory scale Ohmic heater. (1) Hydrogen gas sensor, (2) thermocouple, (3) electrodes: slightly curved electrodes (electrode gap: 9 cm), (4) cooling water inlet, (5) cooling water outlet, (6) removable lid: the electrodes, hydrogen sensor, and thermocouple, are attached. It was tightly clamped to the cell body during Ohmic heating.

The electrodes in the cylindrical reaction vessels are curved. Kulshrestha and Sastry (2003) developed a model for the electric field within the vessel domain by solving Laplace's equation. Except for the electrode edges, the nondimensionalized results showed that the electric field is reasonably uniform within the chamber. Also, continuous stirring in the vessels ensures that the medium receives uniform treatment.

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14 Tubular and Fluid Jet Units

Sami Ghnimi and Luc Fillaudeau

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14.1 INTRODUCTION

The demand for alternative food processing techniques has increased at a rapid rate as manufacturing moves further into the twenty-first century. As technology advances, more efficient equipment can be retrofitted to replace antiquated machinery and processing methods for the food industry. With growing concerns on the safety of food for consumption by humans, a processing technique that is more easily controlled, more efficient, and just as effective as current techniques could revolutionize the food industry in the coming years. Ohmic heating is one of the newest alternative processing techniques to emerge in the last 15 years. Using electric current, food can be pasteurized, fermented, or sterilized in a manner that is equally comparable, if not better, than the current methods of processing.

The Ohmic heating technology was proposed for the first time by Jones (1897). At the beginning of the twentieth century, Anderson and Finkelstein (1919) and Samuel et al. (1927) demonstrated the feasibility of pasteurizing milk by means of the continuous Ohmic heating technology. This process, known as “Electropure,” was a technical and commercial success and by 1930, it was used in approximately 50 milk pasteurizers in five US states and served about 50,000 consumers. Between 1930 and 1970, several works were devoted to the Ohmic heating technology for fast thawing of frozen food and fast heating of cooked dishes such as pizzas, sauces, and hamburgers. Despite the growing interest in this technology since the end of the twentieth century, Ohmic heating has not achieved the expected success for various technical and economic reasons, which include the absence of inert electrode materials and control equipment accurate enough to keep the temperature within the necessary range and sufficiently robust to withstand the conditions of commercial conditions (Kucherenko, 1968; Amatore et al., 1998; Tzediakakis et al., 1999).

During the past decade, new improved electrode materials and equipment designs have become available. The most recent achievements in continuous Ohmic heating are the development of the tubular processes (APV, Raztek and Emmepiemme) for the sterilization of homogenous and particulate foods and the fluid jet unit (Emmepiemme) for the processing of highly viscous liquids (Sastry and Palaniappan, 1992a,b,c; Fryer and De Alwis, 1998; Legrand et al., 2007; Ghnimi et al., 2008,

TABLE 14.1
Technical Parameters of the Ohmic Heating Systems

	APV Baker	Emmepiemme (Tubular)	Raztek Corp.	Emmepiemme (Fluid Jet)
Type of technology	Continuous process	Continuous process	Continuous process	Continuous process
Geometry	Tubular	Tubular	Tubular	Free jet
Type of Electrode	- Platinum-coated electrodes - Intrusive electrodes	- Stainless-steel electrodes - Rising electrodes	Pure-carbon electrodes	Stainless-steel electrodes
Power supply	- Frequency: 50 Hz - E//U	- Frequency: 25 kHz - E//U	- Frequency : 50 Hz - E⊥U	- Frequency: 25 kHz - E//U
Product	Solid–liquid suspension	Solid–liquid suspension	Homogenous liquid	Homogenous liquid

2009a). These Ohmic heating technologies may be widely differing (Table 14.1). Arguably the most successful application of this technology has been in the area of fruit and vegetable processing, and multiphase products.

In this chapter, tubular and fluid jet devices designed to heat Newtonian, non-Newtonian fluids, and food mixtures are mentioned. Technical aspects are discussed and various industrial applications are presented. The encountered difficulties and beneficial aspects are reported.

14.2 TUBULAR UNIT

Recently there has been a great deal of research on the application of tubular Ohmic heating to food processing for a variety of purposes. It has been recognized that the tubular system may have technical advantages over other heat exchangers if the liquid is very viscous, thermally sensitive, or prone to fouling of heated surfaces in the equipment. Most tubular Ohmic heating system configurations consist of three modules: heater assembly, power supply and control panel. Typical continuous commercial Ohmic heating systems for homogenous liquids (Raztek Corp, Sunnyvale, CA, USA) and liquid-particulate mixtures (APV baker, Crawly, UK and Emmepiemme, Piacenza, Italy) are presented in Figure 14.1.

14.2.1 APV BAKER DESIGN

Because all the attempts at commercialization failed due to problems associated with electrode degradation and uneven heating of the product, APV conducted research on several key areas of the technology:

- Electrode arrangement design for such equipment.
- Establishment of safety standards for such equipment.
- Validation procedures to ensure proper sterilization of food products.

These studies resulted in a successful submission in 1991 to the UK Advisory Committee for Novel Foods and Processes to approve the APV heating system for the production of ambient stable low-acid, ready-to-eat meals in the United Kingdom.

Figure 14.2 shows a diagram of a typical APV system. The Ohmic heating column typically consists of four or more electrode housings machined from a solid block of PTFE and encased in stainless steel. Each contains a single cantilever electrode. The column is mounted in a vertical or inclined position with the flow of product in an upward direction. A vent valve at the top of the

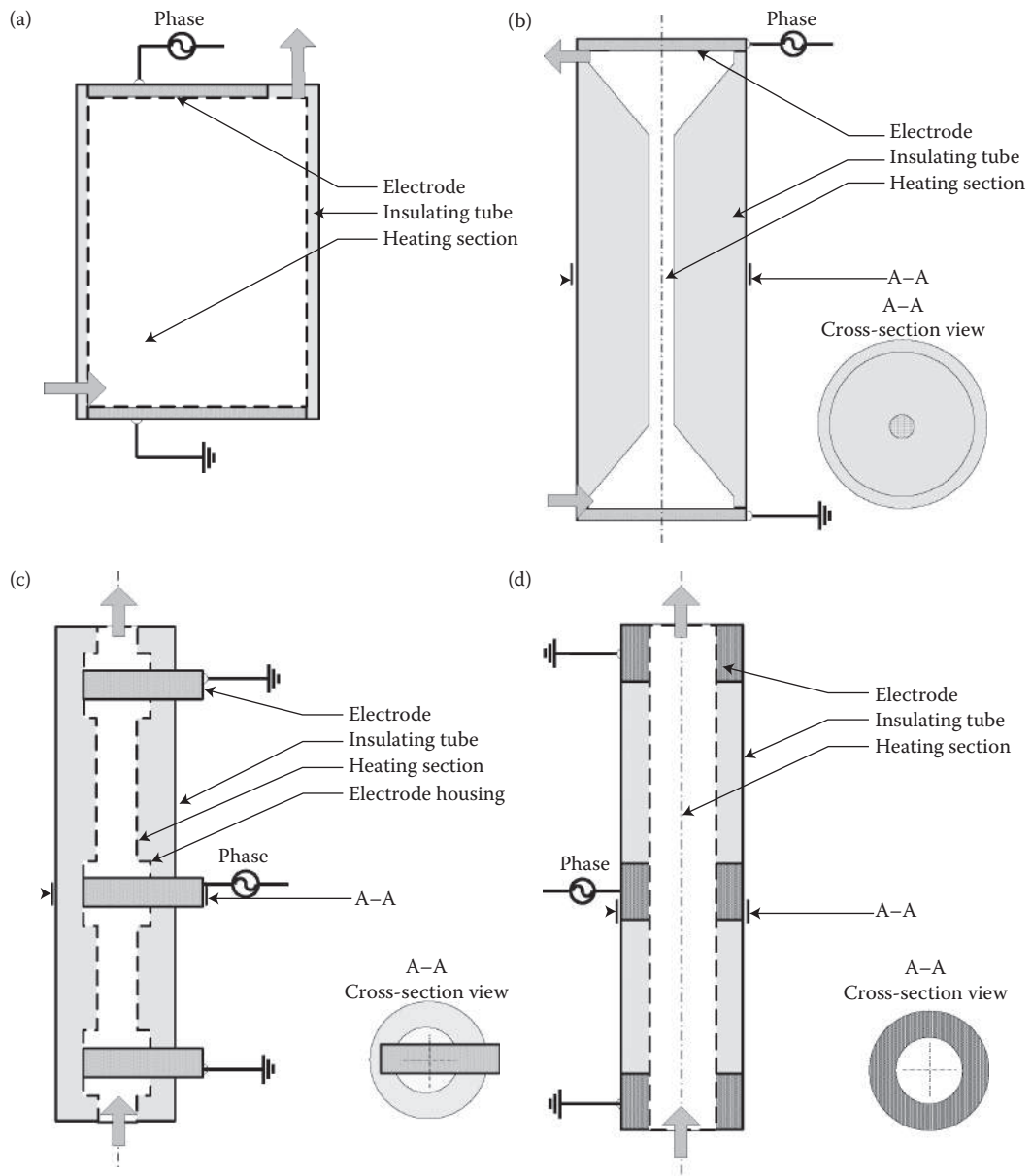


FIGURE 14.1 Basic configurations for continuous tubular Ohmic heaters: (a) Bowl in series: liquid product, (b) Raztek corp. (Tubular, E/LU, perpendicular inlet): liquid product, (c) APV (Tubular, E//U, intrusive electrodes): solid-liquid suspension, and (d) Emmepiemme (Tubular, E//U, rising electrodes): solid-liquid suspension.

heater ensures that the column is always full. The column is configured so that each heating section has the same electrical impedance and hence, the interconnecting tubes generally increase in length towards the outlet. This is because the electrical conductivity of food products usually increases with increases in temperature.

Food is pumped through a pipe containing a series of cylindrical electrodes connected to a 50 Hz three-phase supply. The food material is rapidly heated to sterilization temperature, then passed to a holding section and finally to an aseptic packaging plant. To clean, the power is turned off and the

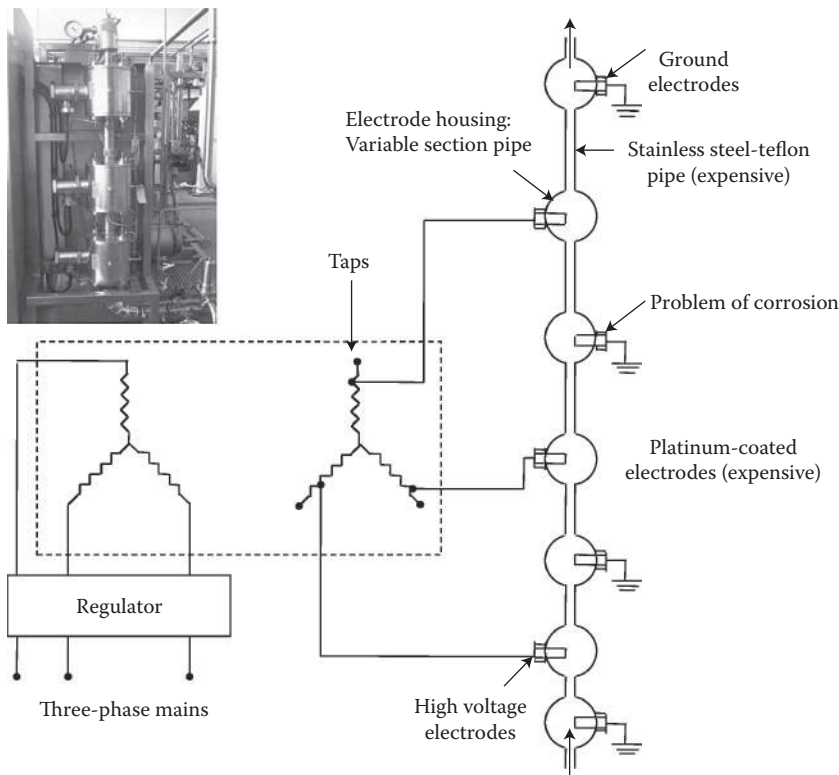


FIGURE 14.2 The “APV” full-scale industrial system block diagram.

plant is rinsed with water. This is followed by a cleansing using a 2% (w/w) solution of caustic soda, recirculated at 80°C for 30 min.

APV plants are supplied with a fully automatic temperature control system. Changes which will affect the final product outlet temperature are inlet temperature, mass flow rate, and the product’s specific heat capacity. In the control system, a microprocessor scans these variables and continuously computes the electrical power required to heat the product, then compares this value with the signal from a power transducer on the output side of the transformer. Feedback monitoring is used to prevent any long-term drift in outlet temperature.

It should be noted that APV electrodes are expensive because they are made of a platinum material to eliminate polarization and contamination. This electrode design induces a variable section pipe, which causes product retention at the vicinity of electrodes and reduces the efficiency of cleaning in place.

The APV process allows food products containing particulates up to 25 mm to be heated to sterilization temperatures up to 140°C in less than 90 s, after which they are cooled back down to ambient temperatures within 15 min. These processing times are significantly shorter than the typical 2-h process cycles for in-can sterilization techniques.

APV produces two commercial systems with power outputs of 75 kW and 300 kW, corresponding to product capacities of 750 kg/h and 3000 kg/h, respectively, for a temperature rise of 75°C in water. Approximate costs for these units in an aseptic system are €1,461,000 to €2,247,000.

The major concerns within the food processing industry:

- The processing of high added value, ready prepared meals for storage, and distribution at ambient temperatures.
- The pasteurization of particulate fruit products for hot-filling.

- The pre-heating of food products prior to in-can sterilization.
- The hygienic production of high, added value ready-prepared meals for storage and distribution at chilled temperatures.

The industrial plants for 300 kW systems (Confidential) installed by APV are mostly in the United States, Japan, and Europe. For the 75 kW systems, many companies used APV system like Sous Chef (UK, Low acid ready meals), Nissei (Japan, High acid fruit products), and Odin Developments Ltd. (Italy, High and low acid ready meals).

Finally, it should be noted that development of applications for the heating system has been primarily undertaken by APV, but has also involved recognized research institutes, associations, and universities such as Campden Food and Drink Research Association, Cambridge University, and Surrey University.

14.2.2 THE “EMMEPIEMME” DESIGN

The Emmepiemme system offers quiet operation for a better working environment, low maintenance due to a reduction in moving parts, and an easy control process that can be started or shut down instantly. An example of an Emmepiemme system can be seen in Figure 14.3. This system

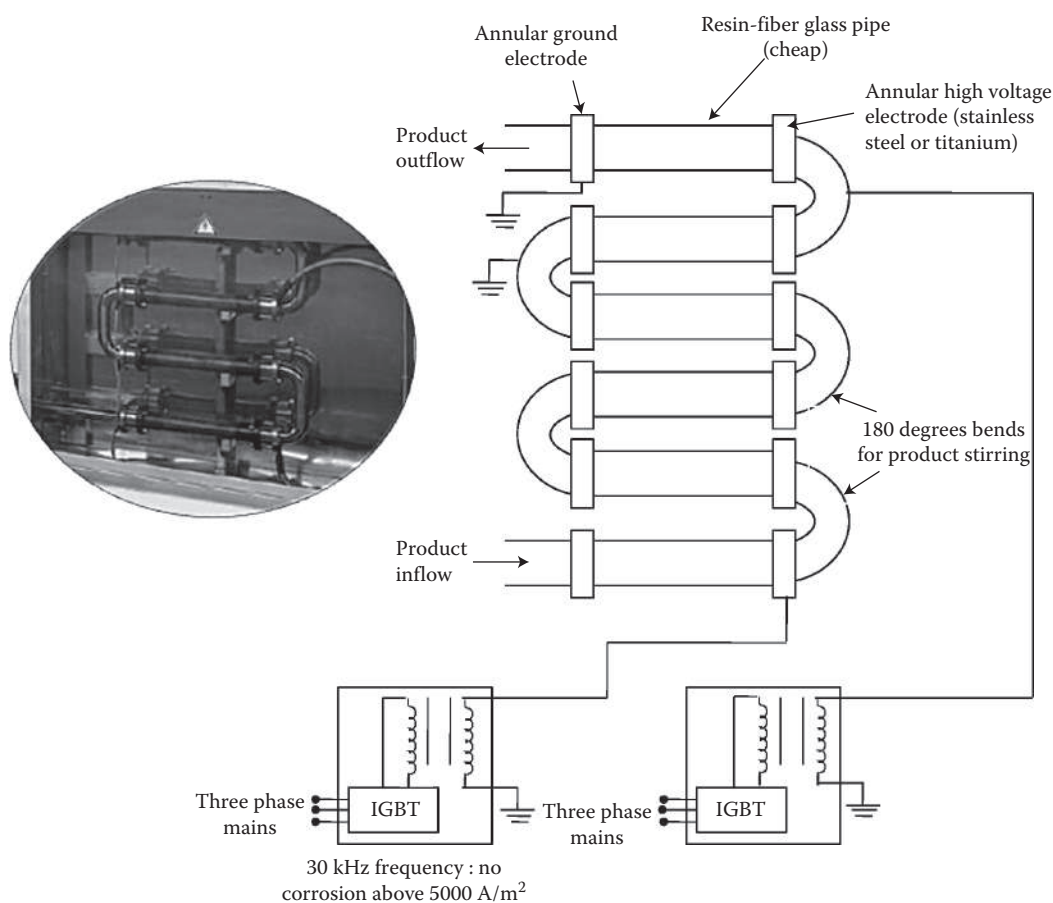


FIGURE 14.3 The “Emmepiemme” full-scale industrial system block diagram.



FIGURE 14.4 A typical Ohmic heater, reproduced with permission from Emmepiemme Srl.

includes many innovations such as the high-frequency power supply (up to 30 kHz) with stainless-steel electrodes (no corrosion above 5000 A/m²) and resin–fiber pipes (cheap).

Emmepiemme (Piacenza, Italy) produces systems in the range of 60–480 kW, for production throughputs of 1000–6500 kg/h. Cost estimates as of 2004 were approximately €68,000 to €248,000, depending on the power output; these estimates are for indication only, as more detailed costing need to be made on a case-by-case basis.

Figure 14.4 shows a diagram of a typical Ohmic heating plant from the point at which the product has been manufactured and is ready for heat processing. The product is pumped through the Ohmic heating column and then enters a holding tube that is designed to ensure that the required minimum level of microorganism lethality has been achieved throughout the fluid volume, based on the target process temperature and time, the length of the holding tube, and the flow properties of the product—in much the same way as would be the case for conventional continuous flow heating systems.

As mentioned in Figure 14.5, the major industrial applications of the Emmepiemme tubular system between 1996 and 2008 concerns the heterogeneous suspensions (25 industrial applications). Few industrial applications concern the homogenous liquids.

Summaries of products processed and industrial plants installed by Emmepiemme SRL are given in Tables 14.2 and 14.3, respectively. The Ohmic heaters installed, by product families is presented in Figure 14.6. The major applications concern the processing of fruits and vegetables.

14.3 FLUID JET UNITS

Although the tubular Ohmic heater appears both simple and advantageous, several difficulties are encountered in its application. The fouling encountered in the vicinity of walls and electrodes and the frequent cleaning of installed units are significant issues that still need to be resolved for the processing of highly viscous products. That is why, a new continuous Ohmic heating apparatus using a fluid jet was proposed by Emmepiemme (Piacenza, Italy) for the thermal processing of homogenous and sensitive products. This new design is based on the elimination of the product–wall interface. It consists of applying an alternative electrical current directly to the falling jet between the two stainless-steel electrodes.

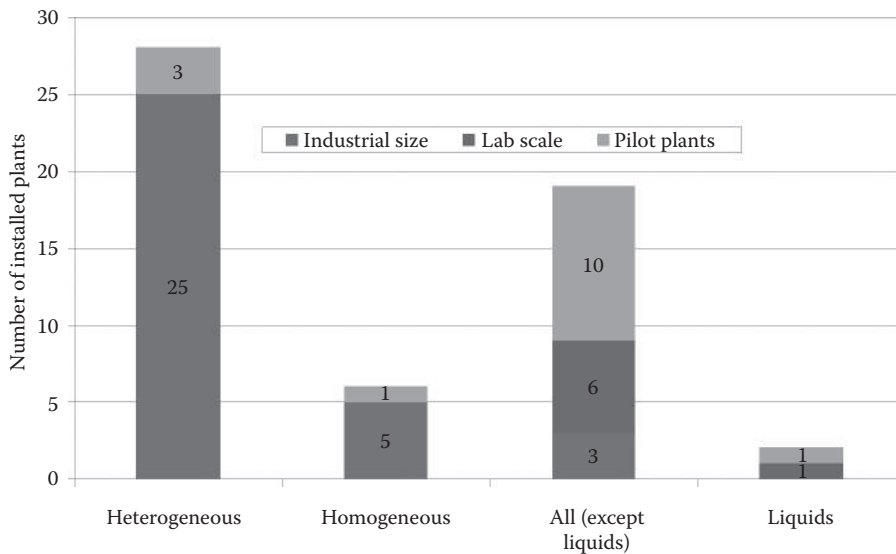


FIGURE 14.5 Tubular Ohmic heaters installed, by product, reproduced with permission from Emmepiemme Srl.

Figure 14.7 is a schematic of a continuous-flow Ohmic heater by using fluid jets. The flow domain consists of a cylindrical glass tube ($D_i = 50$ mm, $L = 155$ mm, $e = 2$ mm) connected to the electrodes, which are tightly held in position using rubber rings and four iron bars with nuts and bolts. The inlet, a round jet through which liquid leaves from the nozzle tip ($D = 13$ mm), is connected to the high-voltage electrode. The outlet, a conical receptacle ($h_c = 45$ mm, $\alpha = 45^\circ$) through which the liquid is taken out, is connected to the ground electrode. The ground electrode has a conical shape, to allow an easier outflow of the liquid and to avoid the vortices and the stagnations of the product. The construction of the Ohmic cell, as that described, allows easy substitution of the glass cylinder with one of a different length and, thus, is adapted for products of various electrical conductivities. This geometry imposed an electrical field parallel to the flow pattern.

TABLE 14.2

Industrially Processed Products in Emmepiemme Equipment

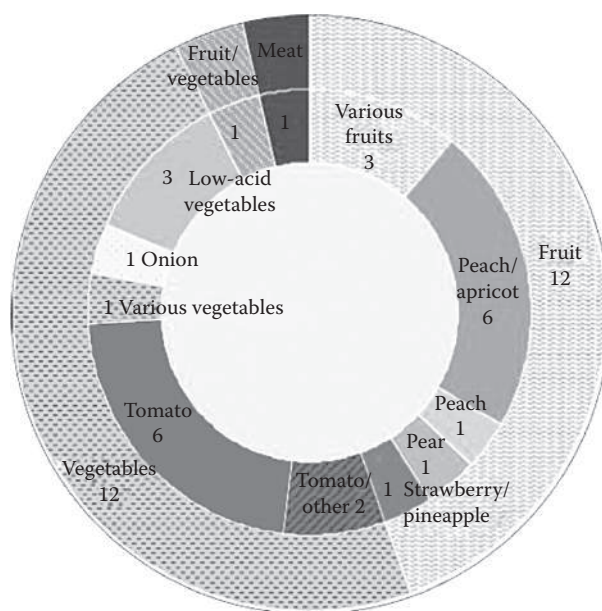
Product (Packaged in Aseptic Bags, 2–20 kg or 200 kg)	Process Temperature (°C)	ΔT (°C)	Heater Power (kW)
Tomato to ready-to-serve sauces	110	50	50
Mange purée	105	20	64
Tomato paste	100	30	64
Diced tomatoes	105	70	70
Tomato purée	120	50	70
Peaches/apricots (dices, slices)	95	50 and 30	100
Diced sweet peppers—zucchini	115	55	150–200
Carrot slices	135	70	100–130
Low-acid vegetables purées	95	30	150
Strawberries (whole, diced)	92	70	30
Onions	—	5	60
Meat sauces	140	55	120

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TABLE 14.3**List of Industrial Plants Installed Globally by Emmepiemme as of 2007**

Country	Installation	Product	Heating Power (kW)
Italy	1994	Aseptic process and filling-tomato sauces and pastes	50
Ivory Coast	1996	Aseptic process and filling-tomato paste and mongo purée	64
Italy (through Simarco)	1996	Aseptic process and filling-fruit slice and dice	100
Greece (through Simarco)	1998	Aseptic process and filling-peach and apricot dices, slices	150
Greece (through Simarco)	1999/2000	Aseptic process and filling-peach and apricot dice, slices and halves	150, 200, 240
Italy	2000	Aseptic process and filling-diced pears, apples	
Italy	2001	Aseptic process and filling-low acid vegetables	150
Mexico	2002	purées	100
France	2002	Strawberries	250
France	2003	Fruit preparations	100
Italy	2004	Processing line for special meat recipes	50
Italy	2005	Aseptic process and filling-plum peeled tomato and tomato dices	480
Italy	2006	New vegetables sauces and special recipes	60
Italy	2006	Aseptic processing line for diced mushrooms and tomato	240
Italy	2006	Aseptic line for tomato dices, pulp and sauces	480
Greece	2006	Tomato sauces and other derivatives	100
Spain	2007	Processing and aseptic filling line—peach, apricot	120
		Processing and aseptic filling line—onion sauces	60

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**FIGURE 14.6** Ohmic heaters installed, by product families, reproduced with permission from Emmepiemme Srl.

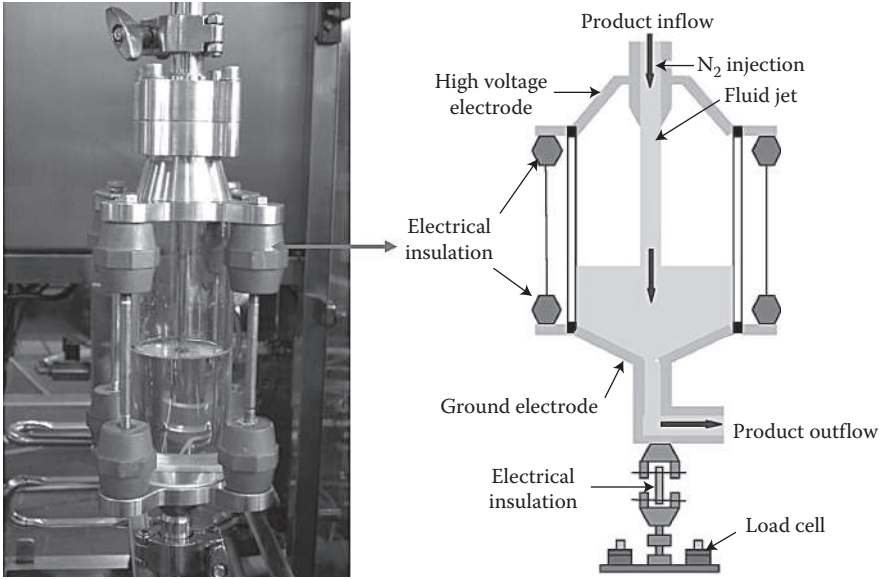


FIGURE 14.7 Schematic of continuous-flow Ohmic heating by using a fluid jet.

The length of the jet is the principal critical process factor in Ohmic heating by using a fluid jet. It is necessary to control and maintain its value constant with time. Indeed, two electro-valves were installed for loading or unloading a part of nitrogen contained in the Ohmic heater. Programmable logic controller software pilots these electrovalves.

A second programmable logic controller was used to calculate the correct heater power to be applied. A fairly typical arrangement of the power circuits and control-signal paths for the Ohmic heater is shown in Figure 14.8. Input signals from inlet temperature and flow rate are used to compute the required instantaneous heater power. Process set-point temperature, fluid level, and product specific heat values are operator-entered. The computed power requirements and fluid level are then compared with measured values to derive an error signal, which is used, in a corrective direction, to increase or decrease the power delivered to the heater.

To prevent the corrosion of the electrodes and the electrolysis of the heating medium, a high frequency power supply that delivers bipolar potential pulses, was used. The frequency is up to 30 kHz with switching voltage up to 3800 V. Both positive and negative pulses of the bipolar pulse output had the same pulse width t_p (μ s), and were equally spaced by adjusting the delay time t_d (μ s), according to the following formulae:

$$T = t_p + t_d \quad (14.1)$$

$$D_p = \frac{t_p}{T} = \frac{t_p}{t_p + t_d} \quad (14.2)$$

where T is the period of the signal (μ s), D_p is the duty cycle (μ s), and therefore the power supplied to the Ohmic cell has the following form:

$$P_{\text{input}} = V_p I_p D_p \quad (14.3)$$

where V_p is the peak voltage (V) and I_p is the peak current (A) delivered by the power supply.

The potential applications of this continuous Ohmic heating technology by fluid jet concerns, first, the heat treatment of dairy products which have been approved. In fact, experiments with

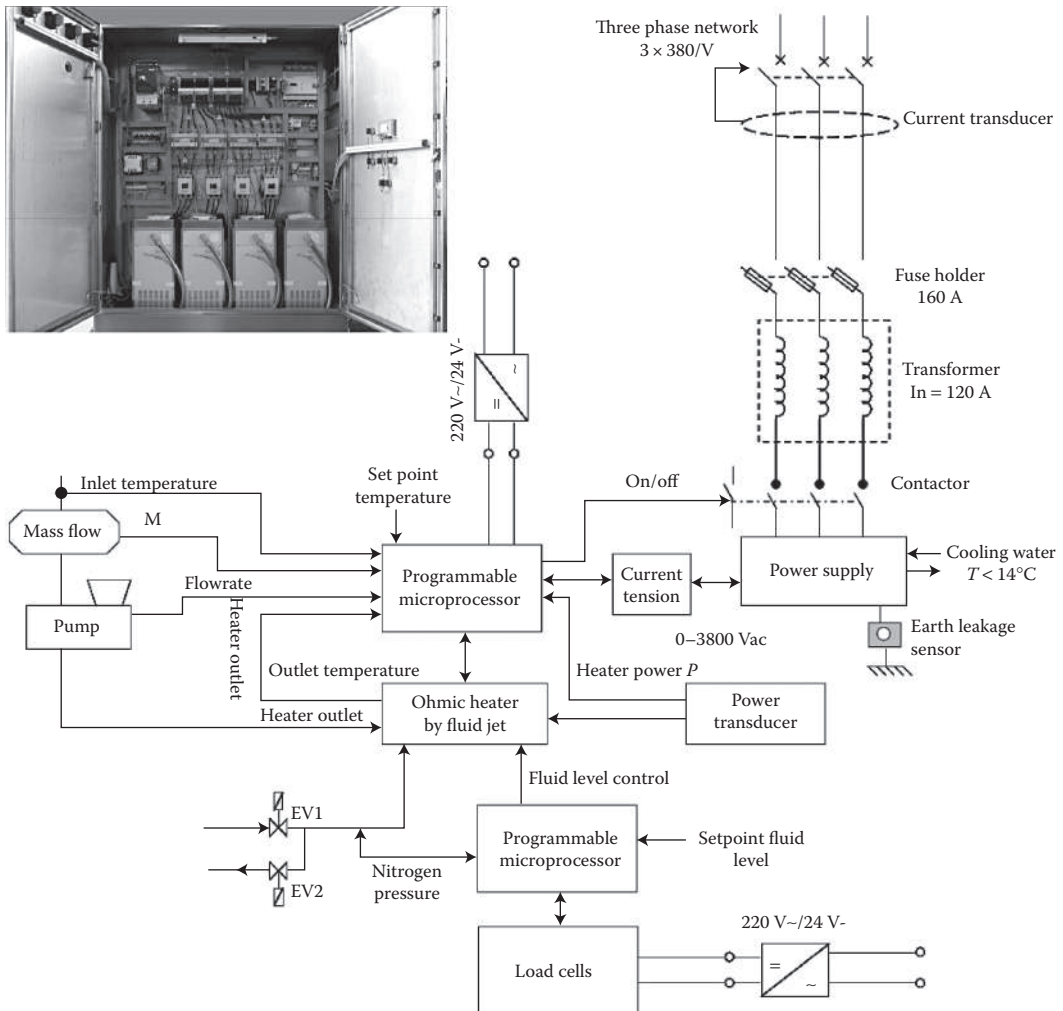


FIGURE 14.8 Power circuits and control-signal paths for the Ohmic heater by using a fluid jet.

when a whey protein solution, designed to mimic dairy products, demonstrated that the fouling thickness at the ground electrode was about 2.2 mm after 4 h (Online fouling/cleaning monitoring by hot-wire technique). However, such deposit thickness remains negligible in cell systems and cannot significantly modify hydraulic, electrical, and thermal performances of the cell apparatus. Cleaning experiments proved that the deposit thickness remains constant with hot water, however when the cell was filled with alkaline solution there was an abrupt drop in the deposit thickness during the first six seconds. Then, a relatively slow decrease was observed until a persistent residual amount of protein fouling developed. All these experimental investigations highlight the potential application of the fluid jet apparatus for dairy product stabilization. However, further studies must be initiated like the analysis of the kinetics of protein deposit formation according to operating conditions such as the inlet temperature or flow regime in the Ohmic cell (Ghnnimi et al., 2009b).

The second potential application of this Ohmic technology concerns the soft pasteurization of poultry blood which is a highly fouling propensity product. Thereby, this highly sensitive product could be valued in food processes, such as the extraction of gelatin instead of being used in animal

TABLE 14.4
Operating Conditions and Microbiological Tests for Poultry Blood Pasteurization

Operating Conditions	Ohmic Heater by Using Fluid Jet	Electrical Tubular Heat Exchanger
Geometry	$L_{\text{jet}} = 130 \text{ mm}$ $\varnothing_{\text{jet}} = 13 \text{ mm}$	$L_{\text{tube}} = 2 \text{ m (12 tubes)}$ $\varnothing_{\text{tube}} = 22 \text{ mm}$
Mass flow rate	260 L h^{-1}	260 L h^{-1}
Reynolds	560	100
Residence time	1 s	140 s
Inlet temperature	35°C	49.4°C
Outlet temperature	60°C	First level: 56.7°C Second level: 57.5°C Third level: 59.8°C
<i>Salmonella</i>	Absence	Absence
<i>Staphylococcus</i>	<100 bacteria/100 mL	<100 bacteria/100 mL
Spores. R.46°C	<10 germs/100 mL	<10 germs/100 mL
<i>Escherichia coli</i>	<100 bacteria/100 mL	<100 bacteria/100 mL
Total aerobic mesophilic flora	<10 ⁵	<10 ⁵

feed. Experiments with two electrical technologies (Ohmic jet and electrical tubular heat exchanger) were carried out.

In regards to the heat treatment with the electrical tubular heat exchanger, the operating conditions are presented in Table 14.4. The mass flow rate was around 260 L h^{-1} , the inlet temperature is around 49.4°C . For the outlet temperature three levels were tested, the first was about 56.7°C , the second was about 57.5°C and the third was about 59.8°C . The Reynolds number was about 100 and the total residence time was 140 s. As mentioned in Figure 14.9, we observed an increase in the

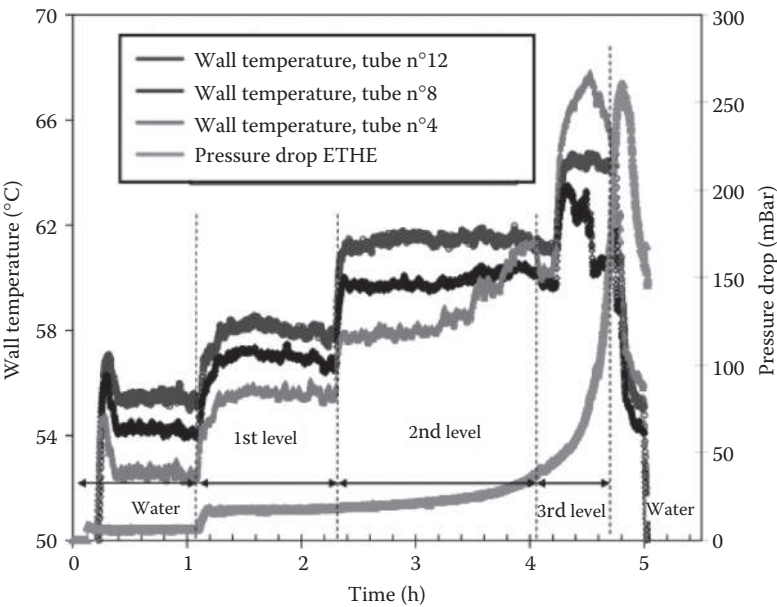


FIGURE 14.9 Evolution of wall temperature and pressure drop during the pasteurization of poultry blood by the electrical tubular heat exchanger.

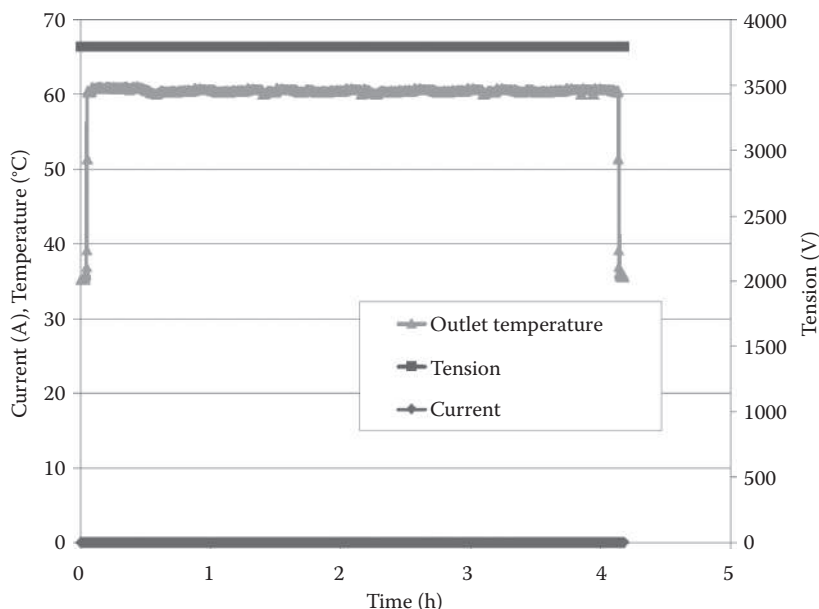


FIGURE 14.10 Evolution of bulk temperature, electrical current and tension during pasteurization of poultry blood by the fluid jet Ohmic heater.

wall temperatures and pressure drop in the tubular heat exchanger, which can be explained by the fouling deposit on the wall of tubes. For this technology, the maximal reached temperature (without fouling), for the poultry blood was about 57°C.

For the Ohmic jet cell, the same flow rate was applied with a temperature difference in the fluid jet of about 25°C in only 170 mm of jet length. The Reynolds number was about 560. However, the other major advantage of this technology is the reduction of residence time in the heating zone. In fact, the total holding time in the fluid jet and receptacle is less than 1 s (Table 14.4). The poultry blood deposit has not been observed due to the absence of product–wall interface and a fine bulk temperature control (Figure 14.10) (Ghnimi et al., 2009b).

After storage of the pasteurized poultry blood during two weeks, the visual appearance and smell were acceptable. Microbiological tests have confirmed the absence of *Salmonella* and even *Staphylococcus* spores, *Escherichia coli* and total aerobic mesophilic flora are in the standards, both for treatment by fluid jet or electrical tubular heat exchanger.

Finally, tests at the experimental station for the canning industry (SSICA—Parma, Italy) approved the application of this new technology for the sterilization of seafood products (pasty products) and pasteurization of liquid egg products. We noted that actually, no commercial application of this technology has been supplied to customers in Europe.

14.4 CONCLUSIONS

The Ohmic heating technology has evolved generations to meet very specific industry issues such as:

- The evolution of the hydrodynamics of heating systems (homogeneous fluid, solid–liquid suspension) to minimize the fouling phenomena.
- The development of new improved electrode materials (titanium, platinum, etc.) and high-frequency power supplies (modular switching units) to prevent the corrosion of the electrodes and the electrolysis of the heating medium.

Actually, the Ohmic heating is of growing interest for the treatment of viscous products and products containing large particles within a liquid phase. There is a renewed interest in Ohmic heating with increasing consumer demands for a minimally processed range of safer, wholesome, and nutritious convenience food products.

NOMENCLATURE

e	tube thickness, m
D	nozzle diameter, m
D_t	glass tube diameter, m
D_p	duty cycle
h_c	cone height, m
E	electrical field, $V\ m^{-1}$
I_p	peak current, A
L	length of the glass tube, m
P_{input}	power supplied to the Ohmic cell, kW
t_p	width of the voltage pulse, μs
t_d	delay time between pulses, μs
T	period of the signal, μs
U	electrical potential, V
V_p	peak voltage, V

GREEK SYMBOLS

α	cone angle, deg.
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SUBSCRIPTS

c	cone
d	delay
i	inlet
o	outlet
p	pulse
t	tube

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Section 6

Modeling of Ohmic Heating

15 Modeling Basics as Applied to Ohmic Heating of Liquid and Wall Cooling

Jean-Pierre Pain and Frans L. Muller

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15.1 INTRODUCTION

Heating is an important part of food processing. Food heat treatments can be divided into two classes: (1) sterilization and (2) cooking (combined with sterilization). The main requirement of food heaters is that the temperature and residence time distributions must be flat as to prevent overcooking, or worse, incomplete sterilization.

Low viscosity liquids like milk or fruit juices are usually sterilized by a HTST process (high temperature short time), keeping changes in taste to a minimum. Fluids that must be cooked are usually more viscous with non-Newtonian rheological behavior and can contain a high fraction of (large) particles. These liquids are usually processed in a scraped heat exchanger, or by canning. When the food particles have large dimensions or poor heat-transfer properties, processing times will be too long, thereby decreasing the product quality.

These days, food industry is moving away from batch-wise processing of food. A continuous process, combined with aseptic packaging allows higher throughputs, better product quality, and a cheaper, more flexible shape of the container. For the complex food fluids the heat treatment is improved considerably when novel systems like microwave heating and Ohmic (direct electrical)

heating are used. Generating heat within the food, these volumetric heating methods depend less on thermal conduction and convection and, hence, cause less temperature gradients. Another advantage is the possibility to use heating tubes with a large dimension and, hence, low shear rates. This allows heating of fragile particles like strawberries.

Ohmic heating consists of an electric alternating current flowing through a moving column in an electrically conducting product. Ohmic heating is a form of volumetric heating. The energy is transformed into heating energy inside the product by the Joule effect, thanks to its electrical characteristics. Ohmic heating can be applied, uniformly and in short times, to homogeneous and heterogeneous products comparable to HTST treatments and, hence, it has many associated advantages: reduced thermal damage of the product, low residence time dispersion, and improved preservation of the sensory characteristics of the incoming fresh material. It is thus possible to stabilize the product without significantly changing the quality criteria (color, loss of vitamins, texture) and nutritional characteristics, or in other words: Ohmic heating can control the reactions at low activation energy and the reactions at high activation energy.

In the early 1980s, first-generation Ohmic heating was the subject of much research in Europe and some Ohmic plants have been sold around the world. The expected benefits were not enough to match the product quality and financial investments.

In the 1990s, the development by Emmepiemme (2009) of a new high-frequency (25–30 kHz) power supply, which included a signal with impulsive waveform (period: 40 μ s), modular design, full-bore electrodes made of stainless steel or titanium (low costs), has revived a “*second generation*” of Ohmic processing equipment, providing improved quality results and financial assets. Meanwhile, their application in industrial and experimental environments has enabled scientists and developers to better understand the coupled phenomena encountered on electrodes and on homogeneous and heterogeneous media at different concentrations of particles. Ohmic heating had industrial applications prior to novel food EU regulation.

This chapter discusses a vertical, tubular Ohmic heater with wall cooling: a collinear heater. Figure 15.1 shows a typical apparatus that consists of two basic elements: the (1) annular ring electrodes that are placed between the (2) spacing tube. Usually several electrodes and tubes are placed in a series. The spacing tube is usually made from glass (on pilot plant), fiberglass, and plastic-lined steel to ensure the electrical current flows only through the liquid product. Most of the heating takes

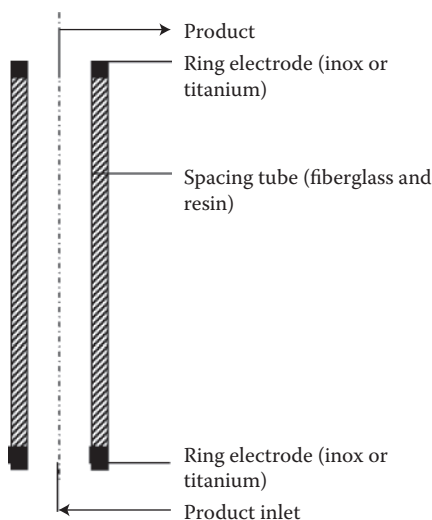


FIGURE 15.1 Schematic view of a collinear Ohmic heater.

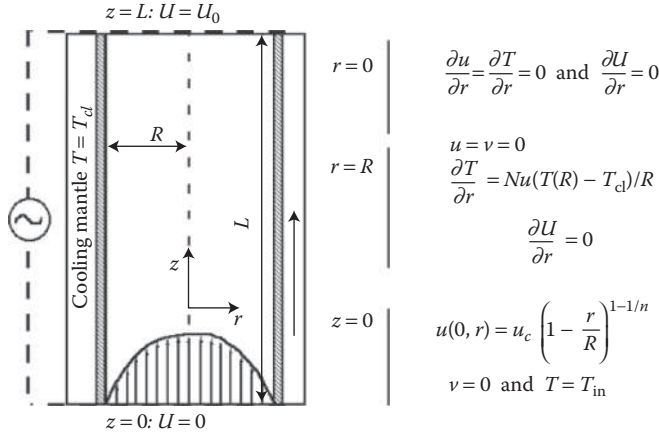


FIGURE 15.2 Model for a collinear Ohmic heater.

place in this tube. Throughout this work the tube is assumed to be a perfect electrical insulator and a single spacing tube is modelled (Figure 15.2).

15.1.1 THE ELECTRICAL FIELD

The annular ring electrode is usually placed in the wall of the column. The electrical field between two electrodes is described by the Laplace equation:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(s r \frac{\partial U}{\partial r} \right) + \frac{\partial}{\partial z} \left(s \frac{\partial U}{\partial z} \right) = 0 \quad (15.1)$$

The electrical conductivity σ is temperature dependent; hence, the solution of the Laplace equation is dependent on the temperature distribution in the spacing tube. The boundary conditions are (Figure 15.2): (i) axial symmetry, (ii) insulating wall, and (iii) top and bottom with fixed potential. The electrical field near the electrode is nonuniform, but it can be shown that the field at the entrance and the exit of the spacing tube is approximately uniform (Muller et al., 1993a), hence boundary condition (iii) is a reasonable assumption.

The heat generated in a fluid element with length Δz in the direction of, and an area ΔA perpendicular to the electrical field E will be subjected to a potential difference $\Delta U = E \Delta z$. The resistance of the element is defined by: $\Delta \Omega = \Delta z / \sigma \Delta A$. Using Ohm's law, the power generated in the element is given by

$$\Delta P = \frac{\Delta U^2}{\Delta \Omega} = s E^2 \Delta A \Delta z = s E^2 \Delta V \quad (15.2)$$

This relationship shows the volumetric nature of the Ohmic heating process. For the nonhomogeneous case ΔP is given by

$$\Delta P = s(T) \left(\left(\frac{\partial U}{\partial r} \right)^2 + \left(\frac{\partial U}{\partial z} \right)^2 \right) \Delta V \quad (15.3)$$

15.1.2 THE TEMPERATURE DISTRIBUTION

The temperature of a fluid element is determined by its residence time in the heater. A lower boundary on the temperature rise may be found from a particle traveling on the centerline with velocity u_c :

$$rc_p \Delta T_{\min} = s E_{\text{est}}^2 \frac{L}{u_c} \longrightarrow \Delta T_{\min} = \frac{L s E_{\text{est}}^2}{rc_p u_c} \quad (15.4)$$

Here E_{est} is an estimate of the field strength; the configuration presented $E_{\text{est}} = Uo/L$. Closer to the wall, the liquid moves slower, hence its final temperature increases more than ΔT_{\min} . The Fourier equation has three terms: (i) thermal conduction in the radial direction, (ii) the volumetric heating term, and (iii) a convection term:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(1r \frac{\partial T}{\partial r} \right) + s(T) \left(\left(\frac{\partial U}{\partial r} \right)^2 + \left(\frac{\partial U}{\partial z} \right)^2 \right) = rc_p \bar{u} \cdot \nabla T \quad (15.5)$$

The conduction in the axial direction is neglected because the term will be very small as compared to the axial convection. The boundary conditions (Figure 15.2) are: (i) the inlet temperature is constant, (ii) axial symmetry, and (iii) a nonadiabatic wall. In previous works the tube wall was taken to be a thermal insulator; that is, the wall was assumed to be adiabatic. However, wall temperatures were shown to increase up to 3 times the average temperature rise (Muller et al., 1993a). Since high wall temperatures lead to fouling, wall cooling is inevitable for volumetric heaters.

To cool, a turbulent co-current flow along the outside of the tube wall is imposed. The temperature of the cooling liquid (T_{cl}) varies only with height. The heat flux into the wall is balanced by the heat transfer to the cooling mantle:

$$-1 \left(\frac{\partial T}{\partial r} \right)_R = h_{\text{cl}} (T_w - T_{\text{cl}}) \quad (15.6)$$

Here T_w is the wall temperature at the inside of the heater. The heat transfer coefficient h_{cl} takes both the heat resistance of the wall, and the transfer from the wall to the cooling liquid into account. Finally, the temperature change in the mantle is found from the energy balance over a section at height z :

$$m_{\text{cl}} \dot{c}_{p,\text{cl}} \frac{\partial T_{\text{cl}}}{\partial z} = 2\pi R h_{\text{cl}} (T_w - T_{\text{cl}}) \quad (15.7)$$

15.1.3 THE VELOCITY PROFILE

The viscous energy dissipation in a liquid is caused by the shear stress (τ) that one layer within that liquid exerts on the next. For non-Newtonian liquids the shear stress is often found from the Ostwald de Waele or power-law model:

$$\tau = -K_m (\dot{\mathbf{g}})^n \quad m_{\text{eff}} = K_m (\dot{\mathbf{g}}_{\text{eff}})^{n-1} \quad (15.8)$$

This empirical relationship describes the shear stress τ as a function of the shear rate $\dot{\mathbf{g}} = \partial u / \partial r$, the consistency index $K_\mu = \partial u / \partial r$ (Pa sⁿ) and the flow behavior index n (dimensionless). An effective

viscosity can be defined by comparing the Newtonian and the non-Newtonian shear stress relation and using some characteristic (effective) shear rate of the system; for a tubular geometry $\dot{\gamma} = u_c/R$. Note that Equation 15.8 reduces to the Newtonian case for $n = 1$. For power-law liquids, the Navier–Stokes equation takes the form of (see Bird et al., 1960):

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r K_m(T) \left(\frac{\partial v}{\partial r} \right)^{n(T)} \right) - \frac{\partial p}{\partial z} - g r (1 - b(T - \langle T \rangle)) = r \bar{u} \cdot \nabla u \quad (15.9)$$

In this equation, included is the natural convection term, which arises from the temperature differences between the wall and the center of the tube. The radial velocities in the system are two orders of magnitude smaller than the axial velocities; viscous dissipation due to the radial velocities is therefore neglected. Instead, the radial velocities are found from the continuity equation. The boundary conditions are (Figure 15.2): (i) axial symmetry, (ii) zero velocity at the wall, and (iii) a fully developed flow at the inlet $u = u_c(1 - (r/R)^{1+1/n})$ (Bird et al., 1960).

15.1.4 TEMPERATURE-DEPENDENT PARAMETERS

The model of the heater as described by Equations 15.1, 15.5, and 15.9 requires the conductivity, viscosity, and the thermal conduction to be known over a range of temperatures (Table 15.1).

For non-Newtonian liquids the consistency index is described by an Arrhenius equation:

$$K_m = K_0 e^{E_a/RT} \quad (15.11a)$$

The flow behavior index n increases with temperature (Muller, 1993b):

$$n = n_{20} + b_n(T - 293) \quad (15.11b)$$

TABLE 15.1
Parameters Used in the Calculation

Property	Symbol	Value	Units
Density	ρ	1000	kg m ⁻³
Specific heat	C	4120	J kg ⁻¹ K ⁻¹
Thermal conductivity	λ	0.6	W m ⁻¹ K ⁻¹
Expansion coefficient	β	5.6×10^{-4}	K ⁻¹
Water viscosity parameters	$K/n/E_a$	0.001/1/7.6	Pa s ⁿ /kJ mol ⁻¹
Glycerol (95%) viscosity parameters	$K/n/E_a$	0.5/1/26	Pa s ⁿ /kJ mol ⁻¹
Carboxy methyl cellulose high-viscosity parameters	$K/n/E_a$	14/1/30	Pa s ⁿ /kJ mol ⁻¹
Liquid electrical conductivity at 25°C	σ_L	0.5	S m ⁻¹
Temperature coefficient	m	0.1	K ⁻¹
Heat-transfer coefficient	h_{cl}	1000	W m ⁻² K ⁻¹
Tube radius	R	0.025	m
Tube length	L	0.75	m
Fluid velocity	v	0.05	m s ⁻¹
Fluid inlet temperature	T_{in}	20	°C
Fluid outlet temperature	T_{out}	45	°C
Mean electrical field	\bar{E}	2000–3000	V m ⁻¹

Data for (K_μ, n) of CMC having medium viscosity 1–8% and CMC having high viscosity 1.5% (Bardon et al., 1988) are used as model liquids. To illustrate food fluids, also included are data for various malt solutions (Singh, 1989) and tomato juice (Pain, 1990). The (K_μ, n) data for all these liquids were measured over a range of 20–80°C. The viscosity of Newtonian liquids is described by an Arrhenius-type exponential equation as well (Perry and Green, 1988):

$$\ln m = A_N + \frac{B_N}{T - C_N} \quad (15.12a)$$

The activation energy for Newtonian liquids, E_a , can be estimated from

$$E_a = RB_N \left(\frac{293}{293 - C_N} \right)^2 \quad (15.12b)$$

Temperature-dependent data of water, sugar (20–60%: Perry and Green, 1988), and glycerol (10–95%: Newman, 1968) solutions were fitted to Equation 15.12.

Over the range of temperatures encountered in the heater, the thermal conductivity may be considered constant. The electrical conductivity is linearly related to temperature:

$$s(T) = s_0 + b_s (T - 293) \quad (15.10)$$

Here b_σ is a positive constant: conductivity increases with temperature due to increased ion mobility. These parameters are strongly dependent on the concentration and the type of ions. As it is the main goal of this chapter to demonstrate the effect of rheological behavior on heater performance, it is assumed that σ_0, b_σ are the same for all liquids. Other physical parameters except (K_μ, n) are as for water, including the properties of the cooling liquid (see Table 15.1).

15.2 THE SOLUTION METHOD

To solve the model, Equations 15.1, 15.5, and 15.9 and the continuity equation are rewritten in a dimensionless form using the following substitutions:

$$\begin{aligned} r^* &= \frac{r}{R} \quad z^* = \frac{z}{R} \quad u^* = \frac{u}{u_c} \quad v^* = \frac{v}{u_c} \\ T^* &= \frac{T - T_{\text{in}}}{\Delta T_{\text{min}}} \quad p^* = \frac{pR}{m_{\text{eff}} u_c} \quad U^* = \frac{U}{U_0} \end{aligned} \quad (15.13a)$$

This leads to the following dimensionless numbers inside the heating tube:

$$Re = \frac{r R u_c}{m_{\text{eff}}} \quad Gr = \frac{g r^2 R^3 b \Delta T_{\text{min}}}{m_{\text{eff}}^2} \quad Pr = \frac{m_{\text{eff}} c_p}{1} \quad Gz = Pr Re R/L \quad (15.13b)$$

And for the cooling section:

$$Nu = \frac{h_{\text{cl}} R}{1} \quad St = \frac{h_{\text{cl}}}{u_c r c_p} \quad (15.13c)$$

Introducing $\sigma^*(E^*)^2$, the dimensionless volumetric heat generation (see Equation 15.3) together, with the above into the balance equations, yields:

$$\frac{1}{r^*} \frac{\partial}{\partial r^*} \left(s^* r^* \frac{\partial U^*}{\partial r^*} \right) + \frac{\partial}{\partial z^*} \left(s^* \left(\frac{\partial U^*}{\partial z^*} \right) \right) = 0 \quad (15.14a)$$

$$\frac{1}{r^*} \frac{\partial}{\partial r^*} \left(r^* \frac{\partial T^*}{\partial r^*} \right) + Gz s^* \left(\frac{L}{R} E^* \right)^2 = Pr Re u^* \cdot \nabla T^* \quad (15.14b)$$

$$\frac{\partial T_{cl}^*}{\partial z^*} = St h (T_w^* - T_{cl}^*) \quad (15.14c)$$

$$\frac{1}{r^*} \frac{\partial}{\partial r^*} \left(r^* m_{eff}^* \frac{\partial u^*}{\partial r^*} \right) - \frac{\partial p^*}{\partial z^*} - \frac{Gr}{Re} (1/\Delta T_{min} b - T^*) = Re u^* \cdot \nabla u^* \quad (15.14d)$$

$$\frac{\partial u^*}{\partial z^*} + \frac{1}{r^*} \frac{\partial v^* r^*}{\partial r^*} = 0 \quad (15.14e)$$

To describe the effect of the temperature field, relative viscosity, and the conductivity parameters are used to take local variations in temperature into account:

$$s^* = \frac{s(T)}{s(T_{in})} \quad \text{and} \quad m_{eff}^* = \frac{m(T, \dot{g})}{m(T_{in}, u_c/R)} \quad (15.15)$$

Note that the relative viscosity must not only be corrected for the local temperature, but also for the local shear rate (see Equations 15.8 and 15.11).

The iterating solution method used to solve the heater model is represented in Figure 15.3. Starting with an estimate of the temperature field, the relative conductivity is calculated, which is then used to find a first approximation of the electrical field. This estimate is then used to calculate a new temperature distribution; this is the TSE loop (temperature, conductivity, electrical field).

Using the temperature field and an estimate of the velocity field, an approximation of the relative viscosities is calculated. Using these, the new flow and temperature fields can be calculated by the

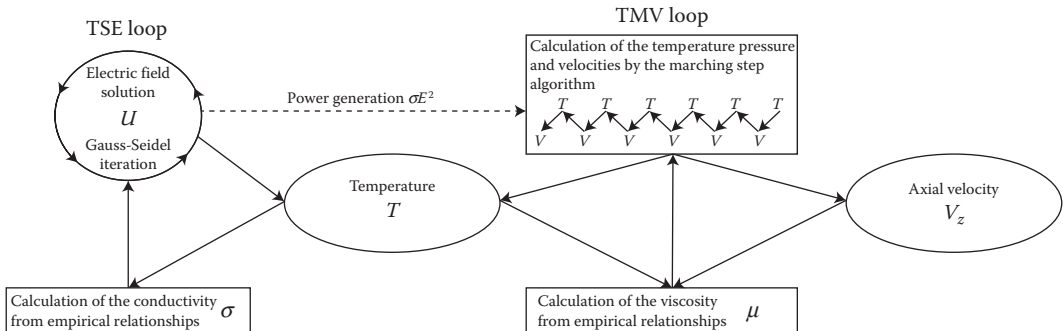


FIGURE 15.3 Diagram of the algorithm used to solve the model of the Ohmic heater.

marching step algorithm (Hornbeck, 1973); the TMV loop (Temperature, Mu, Velocity). The final solution is achieved when further iterations do not significantly alter the solution.

15.3 RESULTS

15.3.1 WALL COOLING EFFECT

Owing to the low velocities, and hence long heating times near the wall, volumetric heaters must be equipped with wall cooling. Even at small cooling rates the maximum temperature in the heater decreases by 30–50%, and is shifted toward the middle of the tube. This implies a considerable reduction of fouling.

A flat temperature distribution is a very important requirement for food heating. Shown in Figure 15.4 are temperature distributions at the outlet for high viscosity CMC, calculated by varying the Nusselt number in the cooling mantle between 0 and 45. The cooling liquid increases less than 2 K in temperature on passing through the mantle, taking up about 10% of the total power input. The cooling causes two important improvements of the temperature profile: (i) the maximum temperature decreases by a factor 2; due to low heat transfer inside the tube even low transfer coefficients in the mantle are effective, (ii) the maximum temperature moves toward the center of the apparatus. This implies that the system will be much less affected by fouling.

15.3.2 EFFECT OF RHEOLOGICAL BEHAVIOR

To study the effect of the rheological behavior on apparatus performance, velocity, and temperature profiles of several liquids were compared (see Figure 15.5). The temperature profile typical for Ohmic heaters causes the flow profile to flatten because of (i) natural convection and (ii) a large viscosity difference between the wall and the center. Although the velocity profiles differ from liquid to liquid, these variations tend to be small, and difficult to characterize. Velocity profiles are mainly determined by the difference in viscosity between the wall and the center of the heater. Non-Newtonian behavior becomes important only when the consistency index (n) that remains is less than 0.6. For a fixed design, performance increases with the products activation energy; higher values of E_a lead to better, more homogeneous heating. For low viscosity liquids ($Gr > 1000$), natural convection improves heater performance.

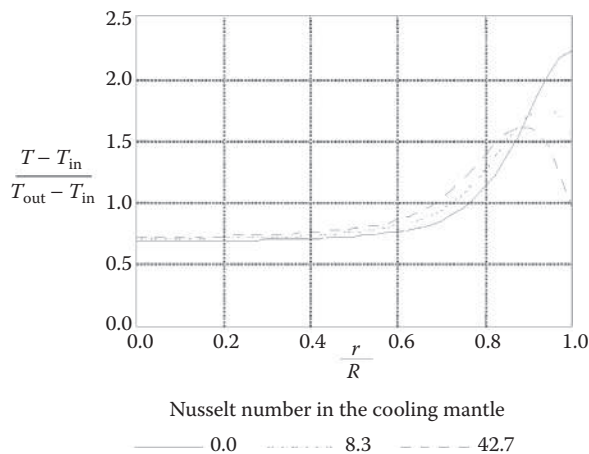


FIGURE 15.4 The effect of wall cooling on the temperature distribution for a 1.5% *h_v* CMC solution.

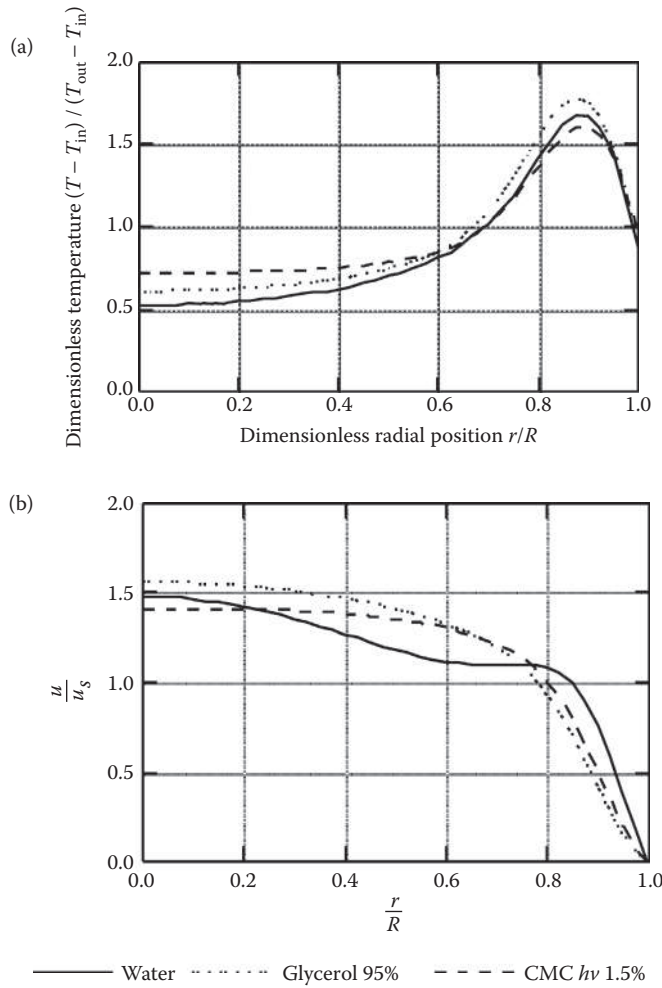


FIGURE 15.5 Flow and temperature profiles for various liquids at the outlet of the heater.

15.3.3 DESIGN OF THE OHMIC HEATER

To compare the performance of Ohmic heaters of different designs or under varying operating conditions, the difference at the outlet between the maximum temperature and the temperature at the center of the column provides a good measure, as it is determined by all factors: liquid type, flow profile, and the heater design (R , L , u_s , T_{out} cooling rate). The parameter ξ

$$\mathbf{x} = \frac{T_{\max} - T_c}{T_{out} - T_{in}} \quad (15.16)$$

will be used to indicate heater performance. Note that ξ tends to zero for flatter temperature profiles.

In Figure 15.6, the performance of an Ohmic heater is given for different liquids. The design parameters are summarized in Table 15.1. In Figure 15.6 only the rheological behavior of the liquids is varied. For values of the Grashof number above 1000, the heater performance improves due to the development of natural convection.

For more viscous liquids, the convection mechanism is unimportant. Heating becomes more homogeneous for lower values of the Grashof number, an improvement due to the viscosity

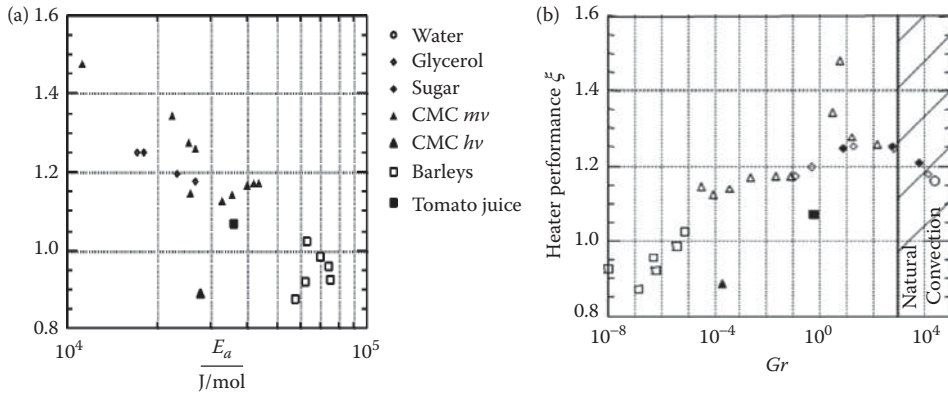


FIGURE 15.6 Heater performance for different liquids in a fixed design.

difference between the wall (μ_w) and the center (μ_c). Higher values of μ_w/μ_c lead to an increase in the shear rate (and velocity) near the wall, and thus improves the performance. The effect of temperature on μ_w/μ_c is best characterized by the liquid activation energy. The alternative plot is therefore ξ versus E_a (Figure 15.6b), which gives a better correlation of performance and rheological behavior than a viscosity-based plot (i.e., Gr).

The difference between the behavior of Newtonian and non-Newtonian liquids is small, but increases when liquids become more shear thinning. For the latter, the flow profile is already “flat” at the inlet of the heater, hence the temperature increase near the wall is less, and performance is improved. Non-Newtonian behavior only has an effect when the consistency index n is less than ~ 0.6 .

So far, the heater design has been constant (see Table 15.1). By varying L , R , or u_s , and keeping rheological behavior and other parameters constant, the effect of the heater design on performance ξ can be studied. Figure 15.7 shows performance ξ as function of the number of Graetz (see

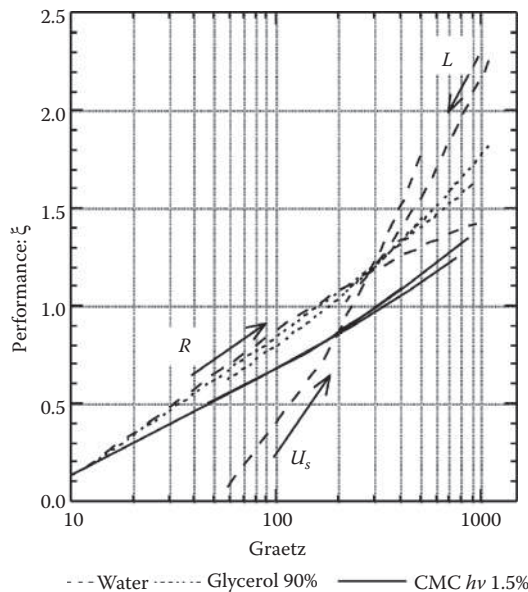


FIGURE 15.7 The effect of heater design of performance. For water the relation between ξ and Gz is dependent on the parameter varied, as indicated. The arrows indicate the direction of increase of the design parameters.

Equation 15.13b and note that Gz is independent of viscosity). For low viscosity liquids the relationship between ξ and Gz is dependent on the parameter varied. This is due to the effect of natural convection. The radius (or Gr) determines whether natural convection will develop ($Gr > 1000$) or not. The extent to which the convection will develop is mainly determined by the liquid residence time (i.e., L or lower u , and may be represented by the number of Graetz).

When operating at $Gr < 1000$, the relationship between an ξ and Gz is well defined and independent of the parameter varied, and it follows from Figure 15.7 that performance is improved at lower values of Gz : that is, smaller radii, longer tubes, and lower liquid flow rates. The Graetz number relates thermal and convective heat transport and may be considered as the ratio between tube radius and the thermal penetration depth. Decreasing Gz corresponds to an increased penetration depth; that is, there is more time for heat to disperse radially, hence the temperature profile will be flatter.

15.4 CONCLUSIONS

This work studied the effect of design and rheological behavior on the performance of Ohmic heaters. Wall cooling is therefore a necessary part of a volumetric heater. A recent patent gives technical solutions to build new Ohmic heaters with wall cooling (Pain et al., 2003). The performance of such Ohmic heaters is best characterized by the difference between the maximal temperature and the temperature in the center of tube. Finally, the Graetz number best expresses the effect of heater design. Designs with a lower Gz will have a more uniform temperature distribution. Lower Gz are achieved by a smaller heater radius, longer tube lengths, or lower liquid throughput.

Second-generation Ohmic heating has proved to be an effective and reliable technology for thermal stabilization of products, allowing in-depth treatment under controlled conditions and resulting in improved quality. Ohmic heating is working on the sensitive products at the temperature, products difficult to treat with conventional thermal heat exchangers such as highly viscous products containing proteins. Researchers are looking an original concept “*heating with cold surface*” in contact with the product gaining new benefits: keep the lubrication layer for high viscous products (continuous cooking) and “*zero fouling process*” (or limited fouling) for sensitive products.

NOMENCLATURE

SYMBOLS

10^{A_N}	empirical constant	Pa s
A	area	m ²
B_N	empirical constant	K
b_n	empirical constant	K ⁻¹
b_σ	empirical constant	S K ⁻¹
C_N	empirical constant	K
c_p	heat capacity	J kg ⁻¹ K ⁻¹
E_a	activation energy	J mol ⁻¹
E_{est}	electric field strength	V m ⁻¹
g	gravitational acceleration	m s ⁻²
h	heat-transfer coefficient	W m ⁻² K ⁻¹
I	electrical current	A
K_μ	consistency index	Pa s ⁿ
L	tube length	m
\dot{m}	mass flow	kg m ³
n, n_{20}	flow behavior index	—
p	pressure	Pa
r	radial coordinate	m

R	tube radius	m
R	gas constant	J mol ⁻¹ K ⁻¹
T	temperature at (r, z)	K
T_{in}	inlet temperature	K
T_{out}	outlet temperature	K
T_w	wall temperature	K
$\langle T \rangle$	mean temperature (at z)	K
U	electrical potential	V
U_0	voltage over the electrodes	V
u	axial velocity	m s ⁻¹
u_s	mean velocity	m s ⁻¹
\bar{u}	velocity vector	
v	radial velocity	m s ⁻¹
z	axial coordinate	m

GREEK SYMBOLS

β	expansion coefficient	K ⁻¹
λ	thermal conductivity	W m ⁻¹ K ⁻¹
ξ	heater performance	dimensionless
\dot{g}	shear rate	s ⁻¹
μ	viscosity	Pa s
η	ratio of cross-sectional areas	
ρ	density	kg m ³
σ, σ_0	electrical conductivity	S m ⁻¹
τ	shear stress	Pa m ²

FOR A SMALL VOLUME ELEMENT

ΔA	surface	m ²
ΔP	heat generation	W
ΔV	volume $\Delta A \Delta z$	m ³
ΔT_{min}	minimal temperature increase	K
Δz	length	m
$\Delta \Omega$	resistance	Ω

DIMENSIONLESS NUMBERS

Gr	Grashof	$Gr = g r^2 R^3 \rho \Delta T_{\text{min}} / \mu_{\text{eff}}^2$
Gz	Graetz	$Gz = Pr Re R / L$
Nu	Nusselt	$Nu = h_{\text{cl}} R / \lambda$
Pr	Prandtl	$Pr = \mu_{\text{eff}} c_p / \lambda$
Re	Reynolds	$Re = r R u_c / \mu_{\text{eff}}$
St	Stanton	$St = h_{\text{cl}} / u_c r c_p$

SUBSCRIPTS AND SUPERSCRIPTS

c	center
cl	cooling
eff	effective
$*$	dimensionless variable

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16 Modeling

Static vs. Continuous Systems

Filiz İçier

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16.1 MODELING OF OHMIC HEATING

To achieve commercial acceptance of a process for the sterilization of low-acid foods containing particulates, it becomes necessary to identify the coldest spot within the system (Sastry and Li, 1996). The problem in safe design is to ensure that all locations of the food have had sufficient time at process temperatures to ensure the elimination of target bacterial spores.

Ohmic heating is considered promising for pumpable liquids, solids, and liquid-particle mixtures because of the rapidity and uniformity of heating. The electrical conductivities of solid and liquid phases as well as the size, shape, and orientation of particles would be expected to play significant roles in the process. As in the case of conventional aseptic processing, the measurement of the particles internal temperatures during continuous flow is difficult; the problems being even more severe for Ohmic heating because of the presence of a strong electric field (Sastry and Palaniappan, 1992a). If the coldest zone is within the liquid, the problem is solved by measurement and monitoring of the fluid temperature. The potentially more dangerous situation arises when the cold zone is within a flowing particle (Sastry and Li, 1996). The future utilization of Ohmic heating by the industry will depend on development of adequate safety assurance protocols.

Fundamental understanding of the process can be obtained using a static Ohmic heater before attempting the process design on the continuous system. The static heater is particularly important because it can approximate the geometry of the continuous heater and clearly demonstrate the effects of operational variables on the heating rates of liquid and particles (Sastry and Palaniappan, 1992a).

Temperature monitoring is critical for the design of the Ohmic heating systems, and equipment sizing critically depends on;

1. Development of suitable heat-transfer models,
2. Verification of these models by experimental methods (either by using biological test organisms and thermal history-type chemical indicators or MRI, etc.).

Since accurate temperature measurement in commercial continuous flow units remains a challenge, it is possible to use mathematical models to gain insight into the process, and to identify potential pitfalls before they can occur in practices (Sastry and Li, 1996). The static heater is a useful device for verification of mathematical models. Systems such as foods and biomaterials are complex, and the accuracy of prediction is not established to the extent that experimentation can be eliminated. The final proof is still experimental, however, if appropriately used, the model can be a valuable guide. Once the accuracy of a model is verified, each simulation serves the function of an experiment. Parameters can be changed and the experiment rerun at minimal cost or time. Another important function is the prediction of outcomes in situations where experimental measurements are difficult or impossible (Sastry and Li, 1996). The problem is even more acute during Ohmic heating because of the presence of an electric field.

One crucial component in understanding the process lies in development of mathematical models, which can be used to simulate various typical, as well as worst case scenarios. It is important that any mathematical modeling tool used for process evaluation be conservative to ensure safety in design (Salengke and Sastry, 2007a). The modeling procedure can be used to simulate different heating conditions for process design and control to save time and money (Ye et al., 2004).

A comprehensive solution to the complete heat, mass, and momentum transfer relations in Ohmic heating is beyond the scope of most modern computation. If the problem is to be formulated in detail, it would require the solution to the equations of continuity, motion, and energy for the fluid, as well as for each individual particle. In practice, simplifying assumptions are necessary to make the problem tractable (Sastry and Li, 1996). On the other hand, if a computer model for the process is available, it could reduce the amount of experimental work needed. Analytical solutions are only possible for very simple geometries and physical properties although numerical methods must be used to simulate the heating of real foods, which are much more complex (de Alwis

and Fryer, 1990b). In some literature, proposed models to predict temperature distributions under specific heating conditions have been experimentally verified with only select points within a system (de Alwis and Fryer, 1990a; Sastry and Palaniappan, 1992a,b; Zhang and Fryer, 1993a, 1995) while some noninvasive temperature mapping techniques (such as magnetic resonance imaging, etc.) enabling fast spatial temperature monitoring during Ohmic heating process had been used to verify the model predictions (Ruan et al., 1999; Ye et al., 2003, 2004).

In this chapter, the modeling procedures of the Ohmic heating process are given in the separate sections for static and continuous systems. The main factors affecting the model predictions and worst-case scenarios are also discussed.

16.2 THE MODELING OF STATIC OHMIC HEATING SYSTEMS

The mathematical formulation involves interdependent electrical and thermal problems, the former involving the determination of the voltage gradient (electrical field strength) and the latter involving determination of liquid and particle temperature fields (Sastry and Palaniappan, 1992a). The iterative scheme is generally used, and the procedure is repeated until convergence.

It is possible to define a sequence of steps that should be followed when using the modeling program to determine processing times (de Alwis and Fryer, 1990b);

1. The region of simulation should be set up to represent the particular geometries that needs to be investigated, together with the appropriate boundary conditions.
2. The variation of temperature with time should be recorded to show critical points where slow heating may be taking place, and to indicate whether the system heating rate is satisfactory, or whether the applied field strength should be changed.
3. The sterilization value or the loss of enzyme activity value of the critical points should be monitored; the minimum processing time required should be reached. Similarly, the cooking value must be controlled whether the maximum processing time allowed is exceeded, if not, cooling should be modeled to determine the final product quality.

16.2.1 VOLTAGE DISTRIBUTION

The basic principle surrounding Ohmic heating is the I^2R energy loss in the resistor. For a constant voltage process, the volumetric heat generation rate (\dot{u}) is (Sastry and Palaniappan, 1992a)

$$\dot{u} = |\nabla V|^2 \sigma \quad (16.1)$$

where V is the voltage and σ is the electrical conductivity of the food material. For a constant current situation, the relation is (Sastry and Palaniappan, 1992a);

$$\dot{u} = \frac{|J|^2}{\sigma} \quad (16.2)$$

where J is the current density.

The voltage distribution within the Ohmic heater can be developed from Maxwell's equations, or by combining Ohm's law and continuity equation for electric current (Sastry and Palaniappan, 1992a; Sastry and Salengke, 1998);

$$\nabla(\sigma \nabla V) + \frac{\partial \epsilon}{\partial t} = 0 \quad (16.3)$$

for the steady state case which is typical;

$$\nabla(\sigma \nabla V) = 0 \quad (16.4)$$

which must be solved over the domain of the sample within the Ohmic heater. Such a solution is generally possible in cases of single particles, but it is difficult for a multi-particle mixture (Sastry and Palaniappan, 1992a). Since it necessitates the knowledge of the location and properties of every particle at all points in time.

The typical static Ohmic heater is a cylindrical chamber filled with the liquid–particle mixture, with the electrodes located at the ends. There are two main approaches used in literature to obtain a simpler estimate of voltage distribution; using the following circuit theory-based approach and Laplace equation approach.

16.2.1.1 Circuit Analogy Approach

The mixture within the model Ohmic heater is considered to consist of a continuous (liquid) and a discontinuous (solid) phase. The equivalent electrical circuit (R) is that of parallel liquid (R_{fp}) and solid (R_{sp}) resistances in a series with a liquid resistance (R_{fs}) (Figure 16.1) (Sastry and Salengke, 1998).

$$R = R_{fs} + \frac{R_{fp} R_{sp}}{R_{fp} + R_{sp}} \quad (16.5)$$

where R_{fs} is the total resistance in the series region, the sum of the resistance to the left and to the right of the parallel region (Salengke and Sastry, 2007a). Resistance could be written for corresponding dimensions and properties;

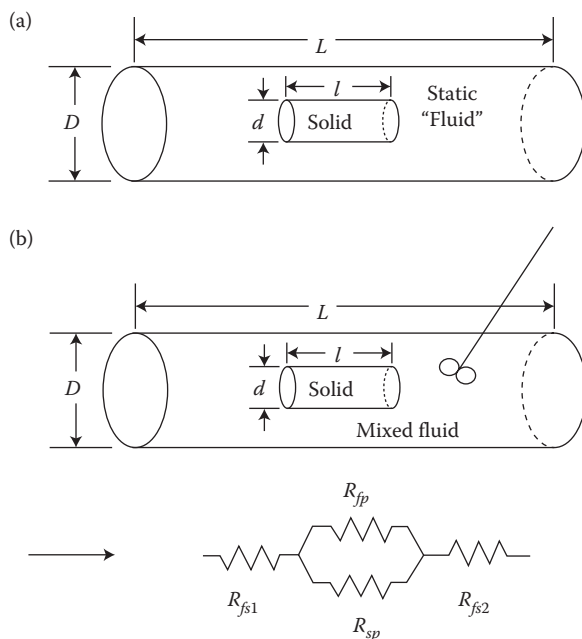


FIGURE 16.1 (a) Situation simulated in LENC model; (b) Situation simulated in CAMF model, showing circuit analogy. (From Sastry, S.K. and S. Salengke, *J Food Process Eng.* 21, 441–458, 1998. With permission.)

$$R = \frac{l}{As} \quad (16.6)$$

A and l are the cross-sectional area and the length of the heater, respectively. On the other hand, cross-sectional areas and the lengths for series and parallel sections are determined separately. It is generally assumed that the area and the length of the discontinuous phase could be determined from the volume fraction of that phase (V_{fs}).

The voltage distribution is calculated assuming that all equi-potential lines are approximately parallel to electrodes (or perpendicular to the tube walls). This is a reasonable approximation when the phases are uniformly mixed (Sastry and Palaniappan, 1992a). The voltage (V) at position x is determined as

$$V = I R(x) \quad (16.7)$$

$R(x)$ is the equivalent resistance up to that position (x) as determined from Equation 16.6.

For situations where the particle location and orientation are accurately known, the equivalent resistance is calculated by separately considering zones containing particles from those without particles. For example for a two-particle case, the heater is divided into zones with particles and without, while allowing at least one particle on either side of each particle to allow distorted equi-potential lines to straighten (Sastry and Palaniappan, 1992a). For zones with particles, the equivalent resistance is calculated as in Equation 16.5. For zones without particles, simply the liquid resistance is taken into account. The voltage was then calculated from a relation similar to Equation 16.7. In such solutions, if the shape of the particles is assumed as cubic, the orientation effects do not significantly influence the electrical field.

For an Ohmic heater containing a mixture of solid and liquid phases of equal electrical conductivities, there exists a uniform voltage gradient along the heater that may be calculated as follows (Salengke and Sastry, 2007a):

$$\nabla V = \frac{V}{L} \quad (16.8)$$

If the solid and liquid involved are of different electrical conductivities, the voltage gradient will not be uniform along the heater and the voltage distributions along the heater may be computed numerically by using circuit analogy approach for incremental sections. For liquid–solid mixtures having appropriate number of incremental sections, an effective electrical resistance (R_j) in each incremental section (j) along the axis of the heater and corresponding voltage gradients across each increment (ΔV_j) can be approximated (Salengke and Sastry, 2007a). The total effective electrical resistance R_{eff} is sum of the electrical resistances for each increment section (R_j) calculated by using Equation 16.5;

$$R_{\text{eff}} = \sum_{j=1}^{j=n} R_j \quad (16.9)$$

The relationship between the effective resistance and the voltage gradient in each increment and the system (Salengke and Sastry, 2007a);

$$I = \frac{\Delta V_j}{R_j} = \frac{V}{R_{\text{eff}}} \quad (16.10)$$

The circuit analogy is useful in determining the voltage drop through the heater sections that are large in comparison with the solids, thereby reducing the computation time involved in the

whole-field simulation. The Laplace solution below is reported to be more suited to resolving local nonuniformities (Salengke and Sastry, 2007a).

16.2.1.2 Laplace's Equation Approach

In this approach it is assumed that the system is stationary, the fluid is nonconvecting, and the electric field is applied along the length of the tube (Sastry and Salengke, 1998).

The voltage (electric field) distribution within the Ohmic heater is calculated by solving Laplace's equation (Equation 16.4) with boundary conditions;

$$V|_{z=0} = V_0 \quad V|_{z=L} = V_L \quad (16.11)$$

The voltage field is functions of the electrode/system geometry, the electrical conductivity distribution and the applied voltage (de Alwis and Fryer, 1990a). At high frequencies, time-varying terms should be included in the voltage equations. If a 50 Hz AC is used by the industrial heater, the current flow obviously varies with time. Under such conditions a displacement current term (J_d) is added to the conduction term (J_c) in Maxwell's equation. It is necessary to prove that time-varying terms can be ignored for the purposes of Ohmic heating, and so the magnitude of the displacement current must be estimated (de Alwis and Fryer, 1990a). Consider a material of electrical conductivity (σ) and the relative permittivity (ϵ_r). The electric field in the material varies sinusoidally;

$$E = E_0 \sin \omega t \quad (16.12)$$

The displacement current and the conduction current terms can be calculated as (de Alwis and Fryer, 1990a);

$$J_c = \sigma E_0 \sin \omega t \quad (16.13)$$

$$J_d = \epsilon_r \epsilon_0 E_0 \cos \omega t \quad (16.14)$$

The magnitude of the ratio is given by (de Alwis and Fryer, 1990a);

$$\frac{J_c}{J_d} = \frac{\sigma}{\epsilon_r \epsilon_0 \omega} \quad (16.15)$$

As the period of the applied voltage is of the order of 10^{-2} s, displacement current can be neglected and conventional rms current values used. The system can be treated as a quasi-steady state using the rms value of the voltage applied between the electrodes. If the medium obeys Ohm's law then at any point the electric field strength E is determined from (de Alwis and Fryer, 1990a);

$$J = \sigma E \quad (16.16)$$

where J is the current flow. At each point in the system, the electric potential V (electric field intensity) is found from (Zhang and Fryer, 1995);

$$E = -\nabla V \quad (16.17)$$

The continuity equation (de Alwis and Fryer, 1990a);

$$\text{div } J = 0 \quad (16.18)$$

equals to Equation 16.4. Since it deals with a medium in which the electrical conductivity is a function of both position and temperature, it differs from the usual form of Laplace's equation (de Alwis and Fryer, 1990a);

$$\nabla^2 V = 0 \quad (16.19)$$

For example, 3-D situation of Cartesian coordinates;

$$\frac{\partial}{\partial x} \left(\mathbf{s}_x \frac{\partial V}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mathbf{s}_y \frac{\partial V}{\partial y} \right) + \frac{\partial}{\partial z} \left(\mathbf{s}_z \frac{\partial V}{\partial z} \right) = 0 \quad (16.20)$$

and for 2-D polar coordinates (Fryer et al., 1993);

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} + \frac{1}{r^2} \frac{\partial^2 V}{\partial \mathbf{q}^2} = 0 \quad (16.21)$$

must be solved with boundary conditions (de Alwis and Fryer, 1990a);

1. On the electrodes, a uniform voltage (Dirichlet conditions)
2. Elsewhere, no current flux across the boundary (homogeneous Neumann conditions)

The solution using weighted residuals and the partition method can be used to solve the resulting set of equations to obtain the field distribution. In the Laplace equation approach, the current flow lines will be curved (Zhang and Fryer, 1995).

Zhang and Fryer (1993a) investigated the more complex effects that occur in systems of higher solids fraction and complex geometries. Zhang et al. (1992) suggested a model which assumed that sections of the fluid could be modeled as representative of the whole. If it is assumed that the distribution of particles in the liquid is uniform, the tube can be divided into a number of "unit cells" each containing a number of particles (Zhang and Fryer, 1995). This approach is common in systems that show symmetry. Each unit cell is identical, so it is only necessary to model one to predict the behavior of the whole. Cell patterns in which particles (cubic or spherical in shape) are distributed on a cubic lattice is possible. Cell size can be adjusted to solve for any solids fraction. Due to internal symmetry, only one-eighth of the cell needs to be simulated. Zhang and Fryer (1995) used ANSYS to solve Equation 16.4 for such cells to predict the voltage distribution of the solid and liquid phases in the mixture.

16.2.2 TEMPERATURE DISTRIBUTION

Once the voltage distribution is available, the heat generation is calculated. The field gradient method is generally used to calculate heat generation in the commercial programs (ANSYS, FEMLAB, FLUENT, etc.). For each two-dimensional triangular element, the field gradient matrix $[E]$ is found and heat generation is calculated by

$$\dot{u} = [E]^T [\mathbf{s}] [E] \quad (16.22)$$

where $[\sigma]$ is the matrix of electrical conductivities. This method is expensive in computer time, involving many matrix manipulations (de Alwis and Fryer, 1990a). For the purpose of calculation, a network theory approach could be used, in which each triangular element is considered as an

isolated network, with nodal voltages known by solution of Equations 16.20 or 16.21 depending on the geometry. The heat generation can be found by

$$\sum_{i=1}^{i=3} V_i I_i \quad (16.23)$$

This method is computationally faster than the field gradient method. de Alwis and Fryer (1990a) discussed that results from the two schemes were effectively identical. Since the initial values of temperatures are known, the problem is thus an initial value problem. The governing differential equation is thus parabolic rather than elliptic (de Alwis and Fryer, 1990a).

16.2.2.1 Single Phase; Liquid or Solid

The heat transfer occurring during Ohmic processing of a solid or liquid food as a single phase is described by the unsteady heat conduction equation with a internal heat generation as given below (Marra et al., 2009);

$$\nabla(k\nabla T) + \dot{u} = \rho C_p \frac{\partial T}{\partial t} \quad (16.24)$$

where \dot{u} represents the heat generation per unit volume (W/m^3) during Ohmic heating (Icier and Ilicali, 2005a);

$$\dot{u} = s |\nabla V|^2 \quad (16.25)$$

where $|\nabla V|$ represents the modulus of the gradient of electrical potential (Marra et al., 2009).

Assuming that equi-potential lines along the heater exist, the volumetric heat generation can be written as (Icier and Ilicali, 2005a);

$$\dot{u} = \frac{s \Delta V^2}{K_c V} \quad (16.26)$$

where K_c is the cell constant, L/A . Since the thermal and electrical conductivities of the liquid or solid foods are temperature dependent, Equations 16.4 and 16.24 must be solved simultaneously. The most important parameter in Ohmic heating of food product, either solid or liquid, is its electrical conductivity behavior. It changes during Ohmic heating depending on temperature and especially, the composition of the food. For liquid foods, σ increases linearly with temperature when subjected to Ohmic heating at representative voltage gradients (Equation 16.27) while the soluble and insoluble solid concentrations affect it nonlinearly (Equation 16.28) (Icier and Ilicali, 2004, 2005b);

$$\sigma = B_1 T + C_1 \quad (16.27)$$

$$s = E_2 (\text{Conc } \%)^{N_2} + B_2 T + C_2 \quad (16.28)$$

The introduction of the voltage gradient term to the electrical conductivity equation (Equation 16.28) results in negligible improvement in the model predictions (Icier and Ilicali, 2005b). For the same voltage gradient and temperature, the electrical conductivity value decreases as the concentration increases (Icier and Ilicali, 2005b). For solid foods, the electrical conductivity–temperature

curve is also linear, up to critical temperatures wherein the chemical and physical changes within the solid food initiate. For minced beef samples, the electrical conductivity was predicted by using a nonlinear temperature-dependent equation for the temperature range of 30–60°C and the voltage gradient range of 10–50 V/cm (Icier and Ilicali, 2005a);

$$s = B3 \cdot T^{N3} + C3 \quad (16.29)$$

The heterogeneous structure of the food materials (such as fat globules and bones in meat products, crystalline structures, multicomponent foods, salt and acid infusion to the product) results in varied electrical conductivities within the food (Tulsiyan et al., 2008). For meat cuts and vegetable stems, fiber or vascular bundle orientation has significant effects (Wang et al., 2001; Sarang et al., 2008). Modeling of the Ohmic heating of such foods or multicomponent foods is difficult due to requirements on using localized electrical conductivities for each heterogeneous region of the food. Thus, the effective (combined) electrical conductivity term can be used to characterize the conductivity of whole foods (de Alwis and Fryer, 1992). The boundary condition for the heat-transfer equation can be taken as the external convective heat transfer loss to the surroundings (W),

$$\dot{Q}_c = UA(T - T_{amb}) \quad (16.30)$$

U is the overall heat-transfer coefficient consisting of possible composite resistance around the Ohmic cell (Icier and Ilicali 2005a; Marra et al., 2009). For initial condition, the entire sample can be assumed at the uniform temperature. For the Laplace equation the following boundary conditions can be assumed: an applied voltage between the two electrodes and a complete electrical insulation of the lateral external sample surface (Marra et al., 2009).

The energy given to the system will be equal to the energy required to heat the sample, plus the energy losses (J);

$$E_{given} = Q_{taken} + E_{loss} \quad (16.31)$$

The energy loss term in Equation 16.31 is the sum of the heat required to heat up the test cell and electrodes, the heat loss to the surroundings by convection, and the portion of the generated heat used for purposes other than heating the food product, that is, chemical reactions, phase change (Icier and Ilicali, 2005a). The performance of the Ohmic system can be determined by using a system performance coefficient (SPC) (Icier and Ilicali, 2005a),

$$SPC = \frac{Q_{taken}}{E_{given}} \quad (16.32)$$

Since low E_{loss} would indicate a system with a high performance, the SPC value will be high. For the SPC value to equal the unity, all the electrical energy given to the system is used to heat up the solid food efficiently (Icier and Ilicali, 2005a). Ye et al. (2004) defined a similar ratio of electricity-to-heat conversion efficiency, which is the convertibility of the electrical energy to heat, and lower than unity. de Halleux et al. (2005) reported that the energy efficiency of the Ohmic heating was $70 \pm 2\%$ for cooking of bologna. The set of equations with their initial and boundary conditions are solved by means of commercial software based on numerical procedures. The implicit or explicit time-stepping scheme is used to solve nonlinear system of equations by iteration approach. The best mesh settings must be found and simulation results must be evaluated by numerical tests with different mesh parameters.

16.2.2.2 Particle–Liquid Mixtures

In general, food particles and carrying fluid exists in food formulations where a particle size distribution occurs in the mixture. The heat-transfer problem should be solved separately for each particle and the liquid, resulting in a computationally prohibitive problem. A more expeditious approach would be to consider the effect of the “average” particle and to assume that the population behavior is similar to that of a collection of particles, all of the average size (Sastry and Palaniappan, 1992a).

The solution consisted of an iterative solution of the voltage field and thermal problems, with the thermal solution being further subdivided into an iterative solution for particle and liquid temperature by the approaches described below.

16.2.2.2.1 Circuit Analogy Mixed Fluid Approach

The typical situation illustrated in Figure 16.1b is used to discuss the particle and fluid temperature distributions in a static Ohmic heater by circuit analogy model. In this approach, the fluid is assumed as having low viscosity permitting rapid mixing, temperature gradients within can be considered small (this has been verified previously by experiment), and the following energy balance may be used on the fluid (Sastry and Palaniappan, 1992a; Sastry and Salengke, 1998; Salengke and Sastry, 2007a).

$$M_f C_{pf} \frac{[T_f^{n+1} - T_f^n]}{\Delta t} = \dot{u}_f V_f + n_p h_{fp} A_p [T_{pm} - T_{fm}] - UA_w [T_{fm} - T_\infty] \quad (16.33)$$

where

$$T_{fm} = \frac{T_f^{n+1} + T_f^n}{2} \quad (16.34)$$

$$T_{pm} = \frac{T_p^{n+1} + T_p^n}{2} \quad (16.35)$$

The volume of the fluid (V_f) and the surface area of the particle (A_p) and the heater (A_w), in Equation 16.33, are calculated as

$$V_f = \frac{\mathbf{p}}{4} (D^2 l_h - n_p d^2 l_p) \quad (16.36)$$

$$A_p = \mathbf{p} D \left(l_p + \frac{d}{2} \right) \quad (16.37)$$

$$A_w = \mathbf{p} D l_h \quad (16.38)$$

The energy generation rate at each point within the liquid can be derived from Equation 16.40 where the temperature dependency of electrical conductivity is linear.

$$\mathbf{s}_i = \mathbf{s}_{0i} [1 + m_i T_i] \quad (16.39)$$

$$\dot{u}_f = |\nabla V|^2 \mathbf{s}_{0f} [1 + m_f T_f] \quad (16.40)$$

The liquid temperature at each successive time increment $(n + 1)$ can be calculated from Equation 16.33. The conduction heat-transfer equation with iterative temperature-dependent internal energy generation could be solved for particles (Sastry and Palaniappan, 1992a; Sastry and Salengke, 1998; Salengke and Sastry, 2007a).

$$\nabla(k_p \nabla T_p) + \dot{u}_p(T_p) = r_p C_{p,p} \frac{\partial T_p}{\partial t} \quad (16.41)$$

with a time-dependent convective boundary condition;

$$k \nabla T_p \vec{n} = h_{fp}(T_{p,s} - T_f(t)) \quad (16.42)$$

the energy generation term for particle is written similarly for liquid (Equation 16.40) (Sastry and Palaniappan, 1992a; Sastry and Salengke, 1998);

$$\dot{u}_p = |\nabla V|^2 s_{0p} [1 + m_p T_p] \quad (16.43)$$

The above problem can be solved using the three-dimensional finite element method in space and Crank–Nicholson finite difference in time (Sastry, 1992). The approach consists of obtaining the weak variation formulations for the above problem, and using polynomial basis functions to obtain the following system of equations (Sastry and Palaniappan, 1992a);

$$\sum_{i=1}^{i=N} M_{ij} \frac{dT_{pi}}{dt} + \sum_{i=1}^{i=N} K_{ij} T_{pi} = F_j \quad j = 1, 2, \dots, N \quad (16.44)$$

For all nonsurface nodes;

$$M_{ij} = \frac{1}{a} \int_v \mathbf{f}_i \mathbf{f}_j dV \quad (16.45)$$

$$K_{ij} = \int_v \left[\nabla \mathbf{f}_i \nabla \mathbf{f}_j - \frac{s_{0p} |\nabla V|^2 m_p}{k_p} \mathbf{f}_i \mathbf{f}_j \right] dV \quad (16.46)$$

$$F_j = \frac{s_{0p} |\nabla V|^2}{k_p} \int_v \mathbf{f}_j dV \quad (16.47)$$

For all surface nodes, M_{ij} is calculated from Equation 16.45 while K_{ij} and F_j are from;

$$K_{ij} = \int_v \left[\nabla \mathbf{f}_i \nabla \mathbf{f}_j - \frac{s_{0p} |\nabla V|^2 m_p}{k_p} \mathbf{f}_i \mathbf{f}_j \right] dV - \frac{h_{fp}}{k_p} \int_s \mathbf{f}_i \mathbf{f}_j ds \quad (16.48)$$

$$F_j = \frac{s_{0p} |\nabla V|^2}{k_p} \int_v \mathbf{f}_j dv - \frac{h_{fp} T_f(t)}{k_p} \int_s \mathbf{f}_j ds \quad (16.49)$$

In the preceding matrix definitions, the basis functions ϕ_i are polynomials chosen such that at the nodal points:

$$f_i(x_j, y_j, z_j) = d_{ij} \quad (16.50)$$

with the property that the Kronecker delta function (δ_{ij}) is unity for $i = j$ and is zero for $i \neq j$ (Sastry and Palaniappan, 1992a). In the above development, the thermophysical properties of solid, although a function of temperature, can be expected to be constant within a single time step, permitting the lumping of k_p , ρ_p and C_{pp} into an effective thermal diffusivity (α). The system of Equation 16.44 can be solved using the Crank–Nicholson algorithm. For solution purposes, the cubic particle can be divided into a workpath of appropriate nodes. Using symmetry considerations, it is necessary to obtain a solution for a corner segment with insulated faces, if available, at the central planes (Sastry and Palaniappan, 1992a). The temperature distribution of the particle–liquid mixture can be determined by iterative solution. All solutions can be fully three dimensional. If the symmetry conditions are available, they necessitate the solution for only one quarter of the heater section. The system of equations had been solved using a 3-D finite element method in space and Crank–Nicholson finite differencing in time by Sastry and Palaniappan (1992a) while using forward differences for the fluid and the Galerkin–Crank–Nicholson method for the solid phase by Sastry and Salengke (1998), and Salengke and Sastry (2007a).

Sastry and Palaniappan (1992a) reported a satisfactory agreement between model predictions using this approach and experimental results obtained for a lower conductivity fluid than solid case. The predictions for similar and higher conductivity fluid than solid cases were in qualitative agreement, but the differences between phases were slightly greater than in the experiment.

16.2.2.2.2 Laplace (Solution) Equation Approach

The typical situation illustrated in Figure 16.1a is used to discuss the particle and fluid temperature distributions in a static Ohmic heater by Laplace model. The cylindrical particle is stationed in the middle of a tube filled with stationary, nonconvecting “fluid” of a different electrical conductivity. An electric field is applied along the length of the tube (Sastry and Salengke, 1998). Since the medium is stationary, the temperature distribution in the heater is governed by thermal conduction with internal heat generated for each phase separately (Equation 16.24) (Sastry and Salengke, 1998; Salengke and Sastry, 2007a). The external boundary condition could be taken as the convection to the surroundings (Equation 16.30).

The influence of the overall heat-transfer coefficient U at the system surface is important. U was assumed as zero in the studies of Zhang and Fryer (1993b, 1995) using the Laplace solution approach. Neuman boundary conditions can be assumed over the full solution boundary (heat losses to the surroundings and at the electrodes) to be zero (de Alwis and Fryer, 1990a). The internal energy generation term is calculated for each phase by using appropriate relations (Equations 16.40 and 16.43).

In some studies (Sastry and Salengke, 1998; Salengke and Sastry, 2007a), the system of equations was solved by the Galerkin–Crank–Nicholson algorithm (a hybrid-spatially Galerkin three-dimensional finite element method in space, temporally Crank–Nicholson finite difference scheme in time). On the other hand, de Alwis and Fryer (1990) had used the fourth-order Runge–Kutta integration for the solution of the resulting set of ordinary differential equations.

16.2.2.2.3 Analytical Solutions

Although the general situation involving solids and liquids of differing electrical conductivity does not have an analytical solution, it is possible to obtain one when the electrical conductivities of both phases are equal (Sastry and Salengke, 1998). A lumped energy balance for the material within a heater is

$$|\nabla V|^2 s_0 [1 + mT] = rC_p \frac{dT}{dt} \quad (16.51)$$

which yields

$$\ln\left(\frac{1+mT}{1+mT_0}\right) = \frac{|\nabla V|^2 \mathbf{s}_0 m t}{\mathbf{r} C_p} \quad (16.52)$$

where T_0 is the initial temperature.

Although the calculation of the temperature distributions in Ohmic systems is complex, approximate calculations can be made in some cases. One of the few analytical solutions possible is the field around a two-dimensional cylinder in an infinite linear field; this solution has already been shown to give a reasonable fit to data in some cases (de Alwis et al., 1989). Two simple limiting case models had been attempted for the limiting cases of zero and infinite thermal conductivity around the cylinder (Fryer et al., 1993).

Case 1: no heat conduction

If it is assumed that the cylinder (Figure 16.1a) is electrically insulating, that the electrical conductivity of the liquid is constant, and that no conductive or convective heat transfer takes place, then Laplace's equation in two-dimensional polar coordinates can be written as Equation 16.42 (Fryer et al., 1993). It can be solved by separation of variables to give for $r > R$;

$$V = E_0 \left(r + \frac{R^2}{r} \right) \cos \mathbf{q} \quad (16.53)$$

where E_0 is the field strength at infinity and R is the cylinder radius. The internal heat generation will be written by combining Equations 16.25 and 16.53;

$$\dot{u} = \mathbf{s} E_0^2 \left[\left(1 + 2 \left(\frac{R}{r} \right)^2 + \left(\frac{R}{r} \right)^4 \right) - 4 \left(\frac{R}{r} \right)^4 \cos^2 \mathbf{q} \right] \quad (16.54)$$

which reduces to Equation 16.55 at the surface of the cylinder ($R = r$) (Fryer et al., 1993);

$$\dot{u} = 4 \mathbf{s} E_0^2 (1 - \cos^2 \mathbf{q}) \quad (16.55)$$

The internal heat generation is maximum at $\theta = 90^\circ$ and zero at $\theta = 180^\circ$ based on the horizontal line ($\theta = 0^\circ$) normal to the electrodes. The basic linear change of electrical conductivity with temperature (Equation 16.27) can be incorporated with Equation 16.55 (Fryer et al., 1993);

$$\dot{u} = 4(C_1 + B_1 T) E_0^2 (1 - \cos^2 \mathbf{q}) \quad (16.56)$$

Since the heat conduction term is negligible in this case, Equation 16.24 takes the form of Equation 16.57 by substituting Equation 16.56;

$$4(C_1 + B_1 T) E_0^2 (1 - \cos^2 \mathbf{q}) = \mathbf{r} C_p \frac{\partial T}{\partial t} \quad (16.57)$$

and integrated to give the temperature at the upper particle surface, $\theta = 90^\circ$ (Fryer et al., 1993);

$$T = \frac{1}{b} \left[(C_1 + B_1 T_0) \exp \left(\frac{4 B_1 E_0^2}{\mathbf{r} C_p} t \right) - C_1 \right] \quad (16.58)$$

However, this approach neglects conduction and convective heat transfer completely. Fryer et al. (1993) discussed that this approach predicted close temperatures to the experimental data for the first 30 s, then predicted the temperature poorly.

Case 2: infinite thermal conduction

In this approach, convective and conduction heat transfer occur infinitely fast (Fryer et al., 1993). Thus, the liquid temperatures are uniform, all of the liquid heats at the same time. The system resistance can be estimated by assuming a uniform electrical conductivity throughout the system, and the temperature–conductivity relationship (Equation 16.27) can be substituted into Equation 16.59 and then into Equation 16.24 (Fryer et al., 1993);

$$\dot{u} = (C_1 + B_1 T)E^2 \quad (16.59)$$

$$(C_1 + B_1 T)E^2 = rC_p \frac{\partial T}{\partial t} \quad (16.60)$$

Fryer et al. (1993) discussed that this approach gave good agreement with experimental data for low-viscosity fluids since the system was well mixed. However, the model over predicted the solution temperature at high temperatures.

Case 3: modeling convection

For intermediate cases, where the rate of heat transfer is neither zero nor infinity neither case 1 nor case 2 will give a good fit to data. Convection effects are included to model the temperature profiles. In the static cell, natural convection is the governing mechanism. Benard convection begins when a critical temperature difference is reached. This is termed as “Rayleigh instability” and is correlated by Rayleigh # (Fryer et al., 1993);

$$Ra = \frac{rgb\Delta Td^3}{\mu\alpha} \quad (16.61)$$

or for power law-fluids having a flow behavior index N and consistency coefficient of K (Fryer et al., 1993),

$$Ra = \frac{rgb\Delta Td^{2N+1}}{K\alpha^N} \quad (16.62)$$

For free convection, the temperature driving force is included in Grashof #, and Nusselt # and is correlated as (Çengel and Turner, 2005);

$$Ra = Gr \cdot Pr \quad (16.63)$$

$$Nu = cRa^m \quad (16.64)$$

where c and m depends on boundary conditions as well as the nature of fluid motion. If convection is included in the energy balance (Fryer et al., 1993);

$$\nabla(k\nabla T) + \dot{u} = rC_p \frac{\partial T}{\partial t} + rC_p v \nabla T \quad (16.65)$$

where v is the convective velocity. Although it is possible to solve Equation 16.65 using a numerical model, it would use an impractical amount of computing time. One alternative approach given by Fryer et al. (1993) is rather than attempting to solve the equation directly, instead define an enhanced thermal conductivity k^* to account for thermal convection.

k^* is based on a Ra criterion such that a critical Ra number is defined by assuming that $Nu = 2$;

$$k^* = k \text{ for } Ra < Ra_{\text{critical}}; k^* = c_{\text{critical}} \left(\frac{Ra}{Ra_{\text{critical}}} \right)^m \text{ for } a > Ra_{\text{critical}} \quad (16.66)$$

$$Ra_{\text{critical}} = \left(\frac{2}{c} \right)^{1/m} \text{ for } Nu = 2 = cRa_{\text{critical}}^m \quad (16.67)$$

The model offered a reasonable fit to the onset of convection and the temperature at the upper surface of the particle, but the fit was poor at other positions (Fryer et al., 1993). The model assumed that convection began throughout the fluid at the same time, while in reality it would have begun at one point and then spread. Fryer et al. (1993) discussed another approach by taking into account the suggestions of Kronig and Ahsmann (1949), who said that the ideas of gravity-induced natural convection may be modified by the definition of an electrical characteristic # (El) which differs from the conventional Gr number by replacing $g = B_1 E^2/d$.

$$El = \frac{\mathbf{r}^2 \mathbf{b} B_1 d^2 \Delta T E^2}{\mathbf{m}^2} \quad (16.68)$$

Any differences in liquid temperature due to an inhomogeneous electric field may also affect particle heating rates. In systems of high Bi number, the heating rate is controlled by internal conduction and does not depend on convection coefficient, so that the boundary condition will be;

$$T_l = T_s \quad (16.69)$$

The analytical solution is suitable in general for simple geometries and conditions such as uniform heating temperature and temperature-independent physical properties. When large temperature differences occur around particles, the use of the bulk temperature to calculate a heating time may well cause difficulties. Reducing the viscosity increases the convection within the liquid and acts to reduce temperature differences. For low-viscosity systems, temperature differences are insignificant. Fryer et al. (1993) discussed that it was possible to assume that the system was well mixed and the liquid temperature uniform for low-viscosity carrier fluids, since it was true both for natural and forced convection. On the other hand, the prediction of the heating rate of viscous materials was difficult. They reported that the presence of a high solids fraction could have reduced natural convection and maintained significant temperature differences in the bulk fluid, especially for high-viscosity systems.

16.2.3 STERILIZATION EFFECTS DISTRIBUTION

Since the process is to be used to investigate the food sterility and the quality during Ohmic processing, some representation of sterilization and cooking effects is required. Three sets of reactions must be considered (de Alwis and Fryer, 1990b);

- Those which lead to sterility
- Those that inactivate enzymes
- Those which affect the quality of the product

Each can be modeled using conventional Arrhenius kinetics; the industry uses quantities such as the integrated lethality “ F_0 ” defined as:

$$F_0 = \int_0^t 10^{T-T_{ref}/z} dt \quad (16.70)$$

where T is the temperature and T_{ref} is the reference temperature (generally 394.1 K), z is the slope of the line of $\log D$ vs. T , where D is the time for a reduction in the amount of microorganisms by a factor of $\log 10$ (de Alwis and Fryer, 1990a). F_0 is widely used as a quantitative measure of the total thermal treatment of an object by both food and pharmaceutical manufacturers.

Equations similar to Equation 16.84, but using different z and T_{ref} , can be used to produce C and E values, to represent the cooking of the material and the loss of enzyme activity, respectively (de Alwis and Fryer, 1990a,b). The aim of Ohmic processing must be to achieve certain values of F_0 and E while minimizing C throughout the solid and liquid phases. A product of the required sterility, but which is not over-processed, must be obtained (de Alwis and Fryer, 1990b).

F value ratio has been used to express the extent by which the liquid is over-sterilized in conventional processing (Ruyter and Brunet, 1973). The representation of F_r allows the heating effect to be compared across the whole system, making it simple to identify regions of under or over-processing (de Alwis and Fryer, 1990b);

$$F_r = \frac{F_{0,liquid}}{F_{0,solid}} \quad (16.71)$$

However, the coldest point cannot be easily defined in an Ohmically heated system; F_r can be difficult both to define and interpret. F_r provides no information about the cooking of a particle. Serious differences arise in the worst case when the particle under heats a less conductive particle parallel to the field, regions of the liquid receive several orders of magnitude more thermal treatment than the particle receives (de Alwis and Fryer, 1990a).

Equations 16.72 and 16.73 are used together to determine whether the process is producing an acceptable product (de Alwis and Fryer, 1990b);

$$\phi_F = \frac{F}{F_p} \quad (16.72)$$

$$\phi_C = \frac{C}{C_{max}} \quad (16.73)$$

where F_p is the design value of microbial sterility and C_{max} is the maximum value of C which can be allowed.

If $\phi_F < 1$ the food is insufficiently sterile; if $\phi_C > 1$, the food is overcooked.

Each point in the food material must be processed for a time longer than t_{min} (the time at which ϕ_F equals unity) to give the required sterility, but for no longer than t_{max} (the time at which ϕ_C equals unity) to ensure the food is of satisfactory quality. The task in designing a process is thus to ensure that the residence times of food in the Ohmic heater lie between these two values during both heating and cooling stages (de Alwis and Fryer, 1990b).

16.2.4 FACTORS AFFECTING TEMPERATURE DISTRIBUTION IN STATIC OHMIC SYSTEMS

16.2.4.1 Particle Size, Shape, and Orientation

A solid piece of either very low or very high electrical conductivity has the potential to be under-processed depending on its size and orientation relative to the electric field. The cold spot is within

the solid when the medium is more conductive, except when the solid size becomes sufficiently large to intercept a large fraction of the current (Salengke and Sastry, 2007a). Under this condition, the cold zone is within the medium at shadow zones immediately in front/back of the particle. When the particle size is small ($A_s/A_h = 0.1$ or 0.2), the coldest zone is within the medium when the particle is more conductive (Figure 16.2). However, at large particle sizes ($A_s/A_h = 0.8$), the particle cold-spot approaches the medium cold spot. Under such condition the static model is still conservative. The cold-spot particle temperature significantly lagged the average (CAMF) and cold-spot (LENC) medium temperature; except when the cross-sectional area ratio (A_s/A_h) was 0.8 for the medium, more conductive case (Salengke and Sastry, 2007a).

Thermal conduction is minimized if the total surface area of the particle is minimized. However, as the aspect ratio of the particle increases, thermal conduction will have an increasing effect. The particles of basically uniform cross section, such as spheres and cubes, displayed little variation in the heating rate with orientation while particles with a larger aspect ratio could experience significant variation in the heating rate (de Alwis and Fryer, 1990a). de Alwis et al. (1989) have studied the heating of particles of constant volume but with different surface areas presented to the field. They found that cubes displayed the lowest differential temperature rise when the solid was less conductive than the liquid. Increasing the edge length can lead to either an increase or decrease in heating rate. The heating rate increases with an increasing cross-sectional area when the solid is less

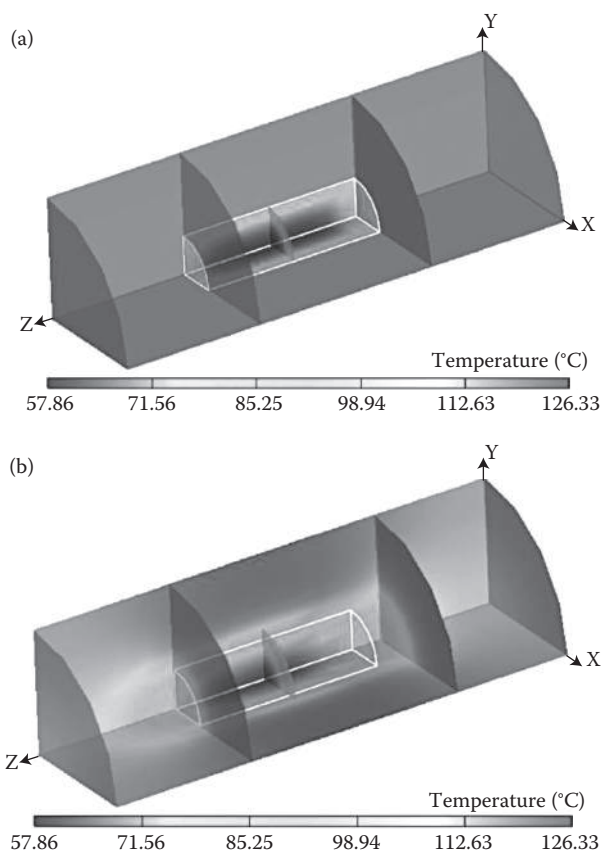


FIGURE 16.2 Temperature distributions within a heater as predicted by (a) the mixed fluid model and (b) static model ($A_s/A_h = 0.1$, $L_s = 3.81$ cm, $\sigma_s/\sigma_f = 1/3$, $t = 150$ s). (From Salengke, S. and S.K. Sastry, *J. Food Eng.* 83, 337–355, 2007a. With permission.)

conductive, but decreases when the solid is more conductive (de Alwis and Fryer, 1992). This is due to the combination of shape and conductivity effects.

A combination of high areas exposed to the fluid and a low thermal path length in the particle gives higher heating rates than would be predicted from purely Ohmic effects (de Alwis and Fryer, 1990a). If it is required to sterilize particles in which the Ohmic heating rate is inherently low, such as those of lower conductivity, the particle should be made sufficiently thin so that it will heat to the required F_0 by conduction alone in the required time (de Alwis and Fryer, 1990b).

When the particle is placed parallel to the electrodes, the more conductive liquid around the edges of the solid shows higher temperatures than the fluid bulk (de Alwis and Fryer, 1990a). This is due to current which is diverted around the solid, as a result of its high resistance; high heat generation. On the other hand, a zone of reduced heating is found across the cell resulting from low field gradients in the more conductive solid and low current densities in the surrounding liquid. When the particle is placed perpendicular to the electrodes, current follows the line of least resistance, resulting in overheating for the solid if more conductive, under heating when it is less conductive than the liquid. These simple circuit analogies can be only used to visualize the reasons for the effects. Furthermore, the heating behavior of a composite is influenced by orientation, as is the case with a single particle. As would be expected, high-temperature regions are seen at either side of the particle perpendicular to the field. When the particle is parallel to the field, both solids provide paths to the flow of current uninterrupted by the other. Current thus finds pathways through each sections of the composite (de Alwis and Fryer, 1992). This underlines the need, in process safety assessment, to conduct both sets of analyses, since the conservatism of a model over one time period may not be sustained, if heating is continued over long durations. Conditions under which the mixed model (CAMF) is more conservative are likely encountered in continuous flow processing of solid-liquid mixtures since the current pumping technology still limits the size of particles that may pass through process equipment (Salengke and Sastry, 2007a).

16.2.4.2 Electrical Conductivity Differences

The critical property influencing the rate of Ohmic heating is the electrical conductivity, which for foods typically increases with the temperature. Sastry and Palaniappan, (1992b) discussed that the electrical conductivity differences between particle and fluid was important for the mixtures having two model particles. The particle center heated faster than the low conductivity fluid. Although heating rates were comparable for the intermediate conductivity fluid, the particle lagged through much of the experiment and then approached fluid temperatures by the end of the heating for the high conductivity fluid case. However, electrical conductivity differences alone do not provide the total explanation; the presence or absence of significant alternative conducting paths through the fluid is an important factor affecting voltage drops and consequently the energy generation rates within both media. It appears that if a particle's electrical resistance within a circuit is a significant component of the overall resistance, the particle will likely heat faster than the fluid even when the conductivity of the fluid significantly exceeds that of the particle (Sastry and Palaniappan, 1992a).

Particles of very high or low conductivity, such as pieces of wood, plastics, and metals have a much more significant effect on the electric field in Ohmic heating than on the temperature field in conventional heating (de Alwis and Fryer, 1992). The iron has a very high electrical conductivity; it acts to suck in much of the current flowing through the system. It might be expected that as a result of this the iron would heat rapidly. However, the potential drop across iron is so low that the resulting heat generation in the solid is less than much of the surrounding food material. The lowest resistance path through the iron passes through the fluid between the iron inclusions. This causes very high temperatures in that region, while elsewhere both the current flow and the temperatures are very low. On the other hand, in the cases of wood or plastic, the amount of current that will pass through the particle is very low, so the amount of heat generated is low, leading to low temperatures. The potential drop across the insulating material is much higher than the liquid. The current flow is diverted around the particle (de Alwis and Fryer, 1992).

The temperatures around the sides of the particle are higher than those of shadow regions. Similarly, the distance between two particles (one of them is insulator) in the mixture can affect the temperature shadows within the Ohmic system (Davies et al., 1999). The 2-D geometry simulations for Perspex block and an egg albumen block in salt water showed the effect of distance between these blocks on thermal field. The Perspex diverts the current around it, and creates a hot spot between the particle and the wall (Figure 16.3) since the electrical conductivity of the egg albumen is higher than Perspex (insulator) and the solution has an electrical conductivity as half of the egg albumen (Davies et al., 1999). Thermal uniformity is approximately 75 mm away from the particle (Figure 16.3). The agreement between data from simulations of Figure 16.3 and experimental values (Figure 16.4) is reasonable. The hot shadow cast by the albumen particle is also seen: the high current flow through the particle leads to a region of high temperature immediately behind it (Davies et al., 1999). The effect of particle electrical conductivity can be dramatic both on its own heating, and more significantly on the surrounding regions of the fluid. Fu and Hsieh (1999) investigated the effects of using electrical conductivity changes during heating of potato- Na_2SO_4 mixture on the simulation results of temperature distributions. They assumed natural convection in the liquid occurring by gravity in a

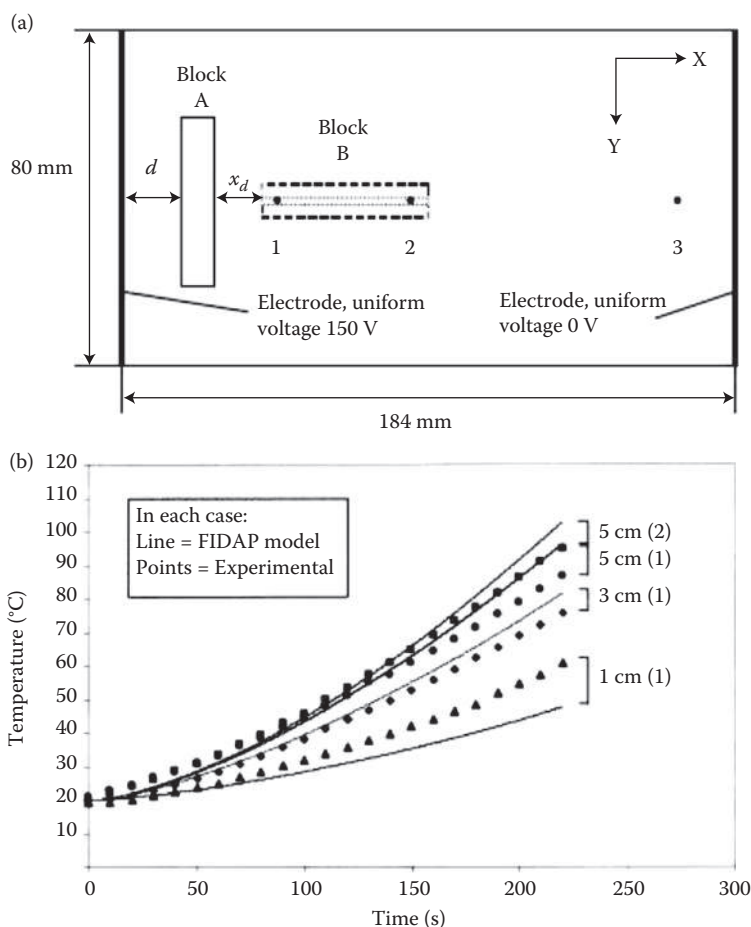


FIGURE 16.3 The effect of the distance between insulating blocks (A and B) placed into the same Ohmic heater on heating rate (a) the plan view of the experimental static system, (b) the Ohmic heating rate of block B (at point 1) with increasing distance x_d (0, 10, and 20 mm). (From Davies, L.J., M.R. Kemp, and P.J. Fryer, *J. Food Eng.* 40, 245–258, 1999. With permission.)

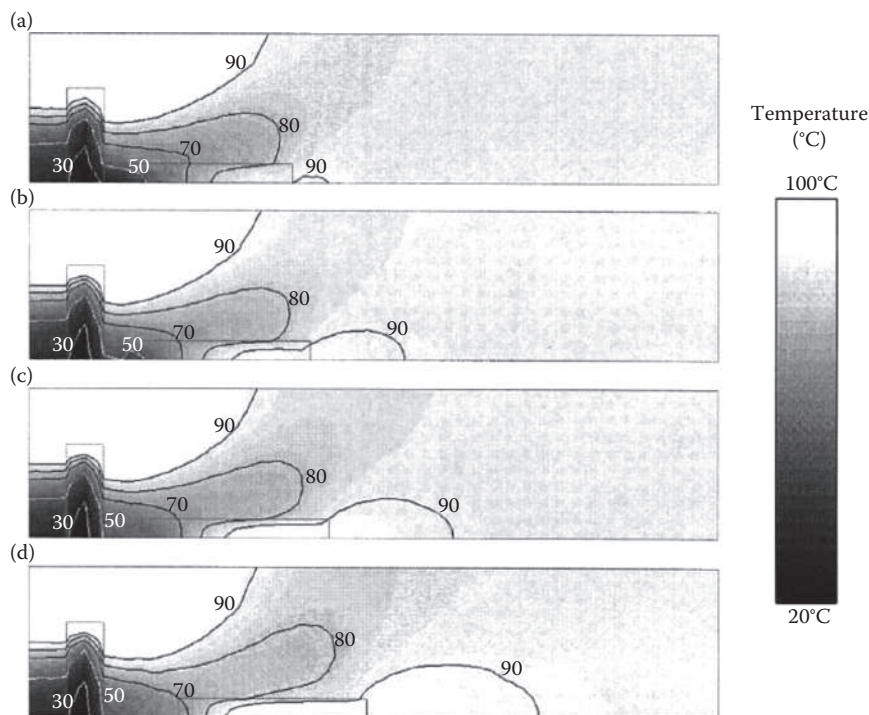


FIGURE 16.4 Modeled temperature distribution for the system after 170 s of electrical heating, when block B is egg albumen. In each case, only the upper half of the vessel is shown due to symmetry. x_d is: (a) 0 mm, (b) 0.5 mm, (c) 10 mm, (d) 20 mm. (From Davies, L.J., M.R. Kemp, and P.J. Fryer, *J. Food Eng.* 40, 245–258, 1999. With permission.)

2-D rectangular static system. They used two parallel bar electrodes, and only one potato slice having dimensions of $1.4 \times 6.2 \times 0.35 \text{ cm}^3$ immersed in 0.03 M sodium sulfate was heated at approximately 1.5 V/cm voltage gradient. They found higher temperatures in the simulation than in the experimental when they assumed insulated boundaries (both electrically and thermally) and constant electrical conductivity. Since the electrical conductivity of the potato slice was lower than liquid, and varied with temperature during Ohmic heating, the temperatures within the solid increased while those within the liquid decreased. On the other hand, the simulated coldest spot location was at the center of the potato slice. They recommended the use of accurate physical property values and valid boundary conditions in simulation to obtain results consistent with experimental values.

Sastry and Salengke (1998) and Salengke and Sastry (2007a) compared LENC and CAMF approach results. The medium was agar gel or acrylamide gel simulating the static situation while it was an agitated aqueous solution of CMC using a vibratory table. A potato particle was used as an inclusion particle. Comparisons of the LENC, CAMF, and analytical solutions confirm that the solutions do indeed yield similar results under equal electrical conductivity situations (Sastry and Salengke, 1998). If the solid is of lower conductivity ($\sigma_s < \sigma_f$), the cold-spot temperatures of the solid are more conservatively predicted by the CAMF model than the LENC model (Figure 16.5a). When the solid is more electrically conductive than the fluid, the LENC model is more conservative than the CAMF model (Figure 16.5b). For the low conductivity solid case, the runaway overheating occurs in a zone completely surrounding the sides of the particle due to current channeling (Figure 16.6). At the same time, the low current density zones immediately in “front” and “back” result in slow heating in these zones. However, since the total interfacial area in front and back is relatively small, the net effect is a more rapid heating of the particle in a static situation. In the mixed situation, it results in

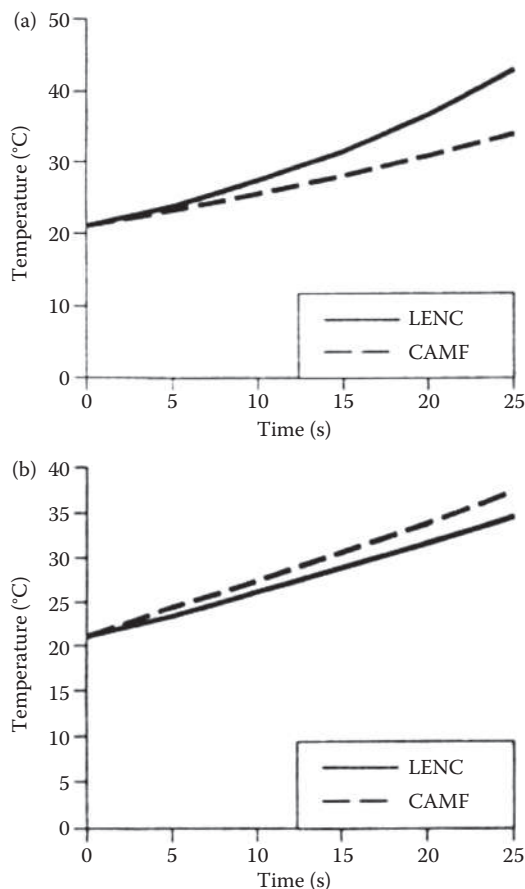


FIGURE 16.5 Particle cold-spot temperature history as predicted by the LENC and CAMF models for (a) $\sigma_s < \sigma_f$, (b) $\sigma_s > \sigma_f$. (From Sastry, S.K. and S. Salengke, *J. Food Process Eng.* 21, 441–458, 1998. With permission.)

intermediate fluid temperatures with no possibility of local overheating. The net heat transfer is relatively small, and the particle heats more slowly. The CAMF predicts a lower energy generation rate than the LENC approach in this situation (Sastry and Salengke, 1998; Salengke and Sastry, 2007a). If the solid is of higher conductivity ($\sigma_s > \sigma_f$), the static situation shows that low heating occurs in the high surface area side region while the front and back tend to overheat (Figure 16.6) (Sastry and Salengke, 1998). The net result is slow heating within the solid. The energy generation predicted by the CAMF approach is also higher than that of the LENC approach in this case. The experimental study of Salengke and Sastry (2007b) presented similar results to simulations in the modeling studies discussed above.

Food materials are naturally inhomogeneous; such as the presence of fat and gristle in meat, seeds in fruit or fibers in vegetable tissue. Inhomogeneity can also arise during processing; such as in the presence of frozen material in partially thawed food (de Alwis and Fryer, 1992). The combine resistance of the particle is dominant in determining the temperatures within the composite; the low constituent will be influential in determining the temperatures. When both solids are more conductive than the liquid, current travels through the whole particle. Overall, only a small region of low conductivity is needed to produce low temperatures. If one component of a composite solid is an insulator, its effect on the heating pattern will be dominant, irrespective of the other component (de Alwis and Fryer, 1992). The most obvious practical cases are the existence of fat in meat samples

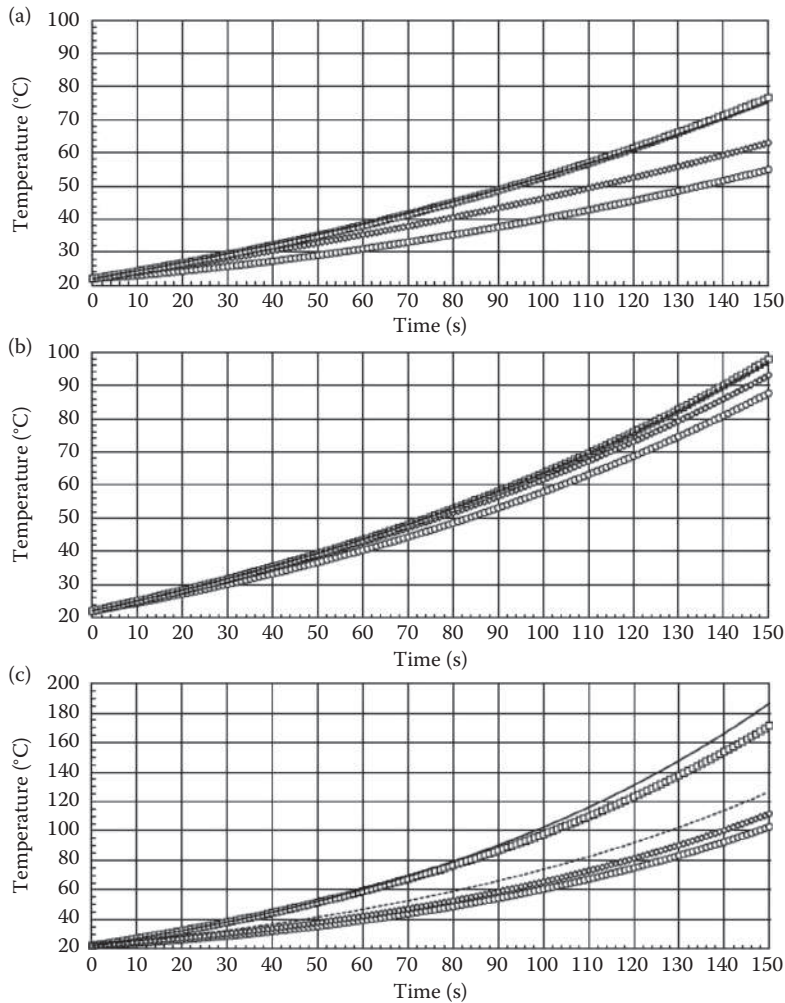


FIGURE 16.6 Comparisons of particle cold-spot and fluid temperatures predicted by the mixed fluid and static models ($A_s/A_h = 0.8$, $L_s = 3.81$ cm), (a) $\sigma_s/\sigma_f = 1/3$, (b) $\sigma_s/\sigma_f = 2/3$, (c) $\sigma_s/\sigma_f = 2$. (From Salengke, S. and S.K. Sastry, *J. Food Eng.* 83, 337–355, 2007a. With permission.)

and frozen foods. These results show that consideration of the particle composition is crucial to determine conditions for achieving sterility.

16.2.4.3 Static or Vibrated Condition

Unlike conventional heating, the fluid motion has the effect of dissipation of hot and cold spots, and actually serves to moderate the heating rather than enhance or retard it (Sastry and Salengke, 1998). The electrical conductivity is the effective factor for cold-spot temperatures in static or agitated conditions. For the particle conductive cases, the worst-case situation occurred under the agitated condition when the particle to heater cross-sectional area was 0.1 but it occurred under the static condition when the ratio was 0.2 (Salengke and Sastry, 2007b). Trends in power inputs and medium heating rates for the heating involving the large particle suggest that a thermal-crossover might be observed after a longer duration of heating, resulting in a more conservative heating under the agitated condition. For the medium more conductive cases, the cold spot was within the inclusion particle and the worst-case heating occurred under the mixed condition (Salengke and Sastry, 2007b).

The extent of fluid mixing that may actually occur in real continuous food processing would depend on the specifics of the flow regime, solids handling, and carrier rheological properties. Studies on fluid interstitial velocity using particle tracking velocimetry have revealed the presence of significant interstitial motion even at Re as low as 9.4 and solids loading as high as 50% (Zitoun et al., 2001).

16.2.4.4 Fluid Viscosity

Motionless viscous fluids can give rise to nonuniformities in heating within the fluid phase surrounding the solids (Fryer et al., 1992). Fluids of identical electrical conductivity but different viscosity with identical amounts of solid particles have been heated Ohmically in batch and continuous flow heaters (Khalaf and Sastry, 1996). In these experiments, the electrical conductivity of solids was lower than that of the fluid. The fluid-heating rate increased with fluid viscosity, and attributed this phenomenon to the lack of the convection in a high-viscosity fluid, yielding high temperatures in regions of maximum current density. If the flow is of low viscosity, permitting rapid mixing, temperature gradients within it can be considered small (Sastry and Palaniappan, 1992a; Fryer et al., 1993).

Fluids of high viscosity do not readily transfer their energy to a low conductivity particulate phase (Khalaf and Sastry, 1996). This results in an increased temperature within the fluid. This eventually causes a temperature difference between the fluid and the solid that more than offsets the effect of low heat-transfer coefficient. The particulate phase heats not only due to its own internal energy generation but also because of gaining heat from a high-temperature fluid. In contrast, low-viscosity fluids having high heat-transfer coefficient tend to exchange heat readily with the particulate phase. The resulting fluid temperatures are lower, resulting in lower electrical conductivity. The net result is slower heating of the low-viscosity system (Khalaf and Sastry, 1996).

Natural convection acts very effective in reducing temperature differences when the viscosity of the solution is low, but it is more ineffective in the case of the viscous solution (Fryer et al., 1993; Davies et al., 1999). Due to the lack of convection in high-viscosity solutions, higher temperatures occurred in the region of maximum current density. These temperatures result in high electrical conductivity, thus a lower system resistance for high-viscosity than for low viscosity solutions. As the same voltage is applied, there is a higher power input and, thus, a higher heating rate is found for high viscosity system. Khalaf and Sastry (1996) discussed that the effect of fluid viscosity on the heating rate were different for batch and continuous heaters. In the static Ohmic heater, the heating rate of the fluid and particles was found to be comparable for the different viscosities. The heating rate of the fluid and particles in the vibrating Ohmic heater was found to increase with increasing fluid viscosity; similar to the mixture with the higher viscosity fluid that heated faster than the lower viscosity fluid in the continuous flow Ohmic heater (Figure 16.7).

Little fluid motion occurs in the static heater, thus, the heat transfer is only slightly dependent on the fluid viscosity. The motion in the heater was sufficient to cause differences in the heat-transfer coefficient between the fluids of different viscosities (Khalaf and Sastry, 1996). The effect of the temperature shadow is clearer in carrier fluids of higher viscosity with less convective mixing (Davies et al., 1999). Especially at high solid fractions, the convective effects are reduced as the viscosity of fluids increased, and maintain significant temperature differences in the bulk fluid (Fryer et al., 1993). In Ohmic heating, unlike conventional heating, the use of viscous carriers can actually enhance heating rather than retarding it. This is a positive finding that has major commercial implications for continuous flow Ohmic heating.

16.2.4.5 Others (Conductive and Convective Effects, Particle Concentrations, System Characteristics, and Computational Effort)

As solids volume fraction increases, the particle temperature tends to increase relative to that of the fluid. The model predictions (CAMF approach) of Sastry and Palaniappan (1992a) have been consistent with experimental data, showing an initial lag for the particle, with a change in relative heating rates after some time. The transition points for particle lagging to particle leading were

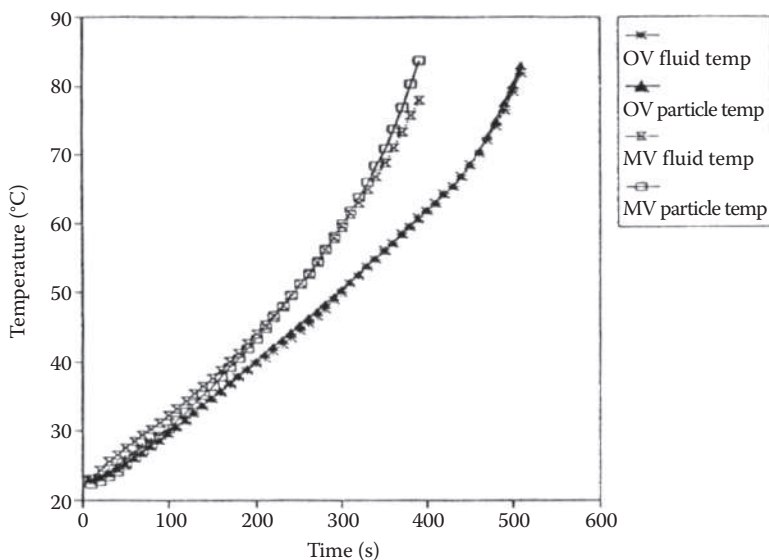


FIGURE 16.7 Heating curves of carrier fluid and particle in the vibrating Ohmic heater, depending on the fluid viscosity (particle is potato and the carrier fluid is CMC having concentration of 0% for OV, 0.6% for MV). (From Khalaf, W.G. and S.K. Sastry, *J. Food Eng.* 27, 145–158, 1996. With permission.)

different between model and experiment. From simulations, when the particle leads to the fluid, the cold spot is typically at the corners, while in the case of particle lagging, the cold spot is at the center. In cases involving transitions from particle lagging to particle leading, the cold spot moves diagonally from the center to the corners.

The use of high solid concentrations is conducive to rapid particle heating, even though the surrounding fluid may have a considerably higher electrical conductivity. This is because as solid concentration increases, the parallel conduction paths through the fluid are increasingly restricted, forcing a greater proportion of the total current to flow through the particles (Sastry and Palaniappan, 1992a). Similarly Fryer et al. (1993) reported that the presence of carrot cubes with a 40% solids fraction in the solution resulted in greater temperature differences than single particle regardless of the solution viscosity. At temperatures above 60°C, the temperature is uniform throughout the fluid.

The model simulations and experimental works have shown that heat loss occurs in the test cell, electrode surfaces, and the surroundings during Ohmic heating of foodstuffs (Icier and Ilicali, 2005a). Improving the system design (better insulation, controlling the external conditions; air temperature and velocity, etc.) could offer to reduce these losses. Icier and Ilicali (2005a,b) have taken into account these losses in the mathematical models by defining the system performance coefficient (SPC) for the Ohmic process. SPC values for Ohmic heating of minced beef samples and fruit juice samples were in the range of 0.36–0.48, 0.47–0.92, respectively, which indicated that 8–64% of the electrical energy given to the system was not used for heating up of the test sample, depending on the type of the food (Icier and Ilicali, 2005a,b). The heat loss to the surroundings by natural convection was very small since the average heat-transfer coefficients were calculated as 3–6 W/m²K while the heat required to heat up the test cell was estimated to be 1.2–10% of the energy given to the system (Icier and Ilicali, 2005a). They concluded that a portion of the electrical energy input could have been used for physical, chemical, and electrochemical changes in the samples. However, it was rather difficult to comment on the exact nature of this loss. This loss did not depend on the voltage gradient applied statistically ($p < 0.05$). The Ohmic heating time predictions of the mathematical model with a zero loss term, t_{adb} , are lower than the experimental results (Table 16.1). Considering the SPC values, the model predictions gave better agreements with experimental data

TABLE 16.1

Comparison of the Ohmic Heating Time Predictions of Mathematical Models Taken into Account of the Heat Losses in the System with the Experimental Data

Voltage Gradient (V/cm)	Q_{taken} (J)	Q_{given} (J)	SPC	t_{exp} (s)	t_{adb} (s)	t_{mod1} (s)	t_{mod2} (s)
The Minced Beef Samples Having Lower Fat Content (mbL)							
10	1508	3864	0.390	273	104	267	270
20	1458	3626	0.402	64	25	61	63
30	1712	4119	0.416	34	13	31	32
40	1613	4279	0.377	16	6	15	15
50	1777	4993	0.356	11	4	11	11
The Minced Beef Samples Having Higher Fat Content (mbh)							
10	1637	4562	0.359	370	133	370	370
20	1575	3712	0.424	82	34	81	81
30	1662	3750	0.443	36	17	38	37
40	1677	3674	0.456	20	9	18	18
50	1707	3580	0.477	12	5	10	10
The Tylose Samples Having 0.5% Salt Content (tyl05)							
10	1680	3975	0.423	310	140	331	326
20	1700	3404	0.500	73	35	69	70
30	1700	3633	0.468	32	16	34	34
40	1554	3371	0.461	19	9	19	19
50	1875	4297	0.436	11	5	11	11
The Tylose Samples Having 0.67% Salt Content (tyl067)							
10	1681	3694	0.453	239	118	259	254
20	1694	3210	0.528	53	28	53	53
30	1643	3476	0.473	28	13	28	28
40	1674	3627	0.462	16	7	15	15
50	1644	4005	0.411	9	4	9	9

Source: From Icier, F. and C. Ilicali, *J. Food Eng.* 69, 67–77, 2005. With permission.

(Table 16.1). Similarly, the use of concentration-dependent electrical conductivities and SPC values in the modeling of the Ohmic heating of fruit juice samples improved the agreement of model predictions (Icier and Ilicali, 2005b). Ye et al. (2004) discussed similarly that the use of electricity-to-heat conversion efficiency improved the accuracy of the model prediction.

Marra et al. (2009) investigated the effect of the external overall heat-transfer coefficient on the temperature distribution of the homogeneous solid food (potato puree) during Ohmic heating (Figures 16.8 and 16.9). As shown in Figure 16.8, $U = 5 \text{ W/m}^2 \text{ K}$ gives even temperature distribution with no more than 3 K among the hottest and coldest areas while $U = 10 \text{ W/m}^2 \text{ K}$ gives colder zones in the proximity of external surfaces, and with sliced corners 6 K colder than the sample core (Marra et al., 2009). Simulation results given in Figure 16.9 show the role of heat-transfer boundary conditions in the development of heating patterns within the solid sample. When U is taken equal to zero, this represents perfectly insulated conditions and no other losses, which approaches higher SPC values discussed in Section 16.2.2.1, and uniform heating within the sample. Marra et al. (2009) discussed the worst agreement between the model predictions and experimental measurements was

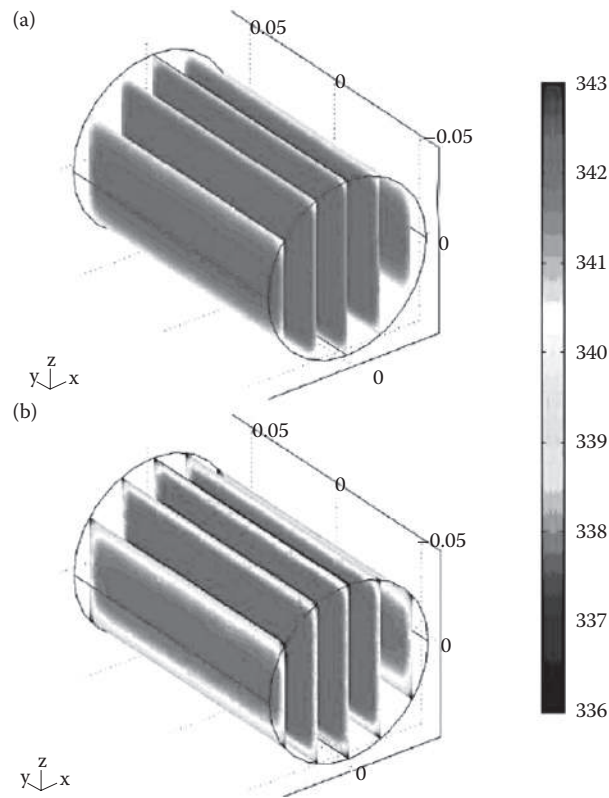


FIGURE 16.8 Slice plot of simulated temperature within the mashed potato cylinder heated Ohmically, for the following conditions: applied voltage set point 100 V, initial temperature 279.15 K, external temperature 286.15, after 150 s, overall heat-transfer coefficient (a) 5 W/m² K, (b) 10 W/m² K. (From Marra, F. et al., *J. Food Eng.* 91, 56–63, 2009. With permission.)

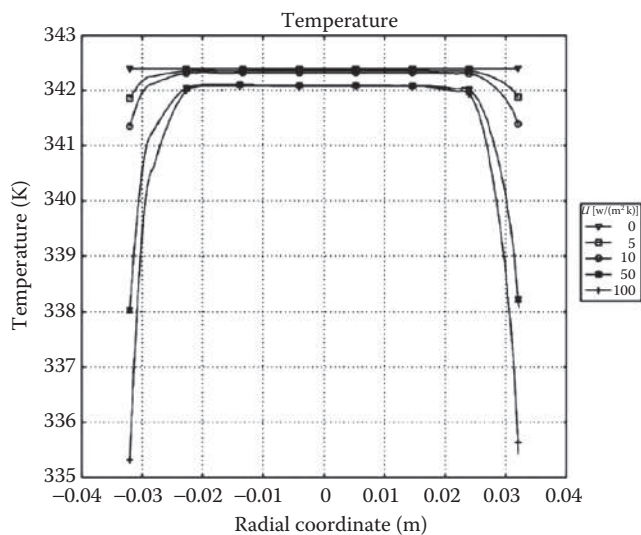


FIGURE 16.9 Temperature plots predicted along the radial coordinate in the planar center of the mashed potato cylinder, as a function of different values of overall heat-transfer coefficient U . (From Marra, F. et al., *J. Food Eng.* 91, 56–63, 2009. With permission.)

the thermocouple positions closer to the external surface at the start of the process. The greatest error varied between 2.63 and 4.65 K for different overall heat-transfer coefficients.

Jun and Sastry (2005) developed a package made of flexible pouch materials powered through a pair of metal foil electrodes extending out. They used a 2-D thermal-electric model to optimize the design and layout of electrodes to ensure uniform heating of the food products (e.g., International space shuttle menu such as chicken noodle soup and black beans). They assumed there was no fluid motion in the static system of a microgravity environment, uniform temperature profiles along the package length, product in a single phase, and negligible heat losses. Three different electrode configurations (pouches a, b, and c in Figure 16.10) have been developed. However, “field overshoot” occurs at the isolative boundary due to the area adjacent to the electrode edge, which is closer to the opposite electrode, causing higher values of field strength. The existence and strength of field overshoot is a key factor dominating the thermal performance inside the package. The 2-D dynamic model predicts thermal distributions that are in good agreement with the experimental data with a minimum R^2 of 0.80 (Jun and Sastry, 2005). The right-hand side of Figure 16.11 shows the cold zones inside the packages, which are the areas covering the temperature distribution between 12°C and 40°C. Pouch b with V-shaped electrodes is expected to be more likely to perform uniform heating of black beans within the package. It was reported that the predictive accuracy was typically lower at each end of the package, wherein the electric field strength is weakened (Jun and Sastry 2005).

The choice of the numerical method in modeling of Ohmic heating processes is crucial. In general, a finite element method has been selected due to its ability to model complex geometries by the correct specification of elements, boundary conditions, and the association of nonlinear material physical properties with each element (de Alwis and Fryer, 1990a). On the other hand, this technique requires a large amount of computer storage and takes a longer time to run than the finite difference technique. Due to limitations on storage and computing time, a 2-D simulation could have been presented in earlier stages. Input data were prepared using an automatic mesh generation scheme and post processing used locally written routines (de Alwis and Fryer, 1990a).

The mesh number used in computer simulations must be reoptimized whenever the size of the solid particle immersed into the fluid is changed. Salengke and Sastry (2007a) discussed the importance of mesh refinement in the temperature distribution in the mixture involving an inclusion particle of 0.0381 m length and 0.0229 m diameter. For the mixed model (CAMF), increasing the number of elements and nodes from 400 elements (451 nodes) to 528 elements (598

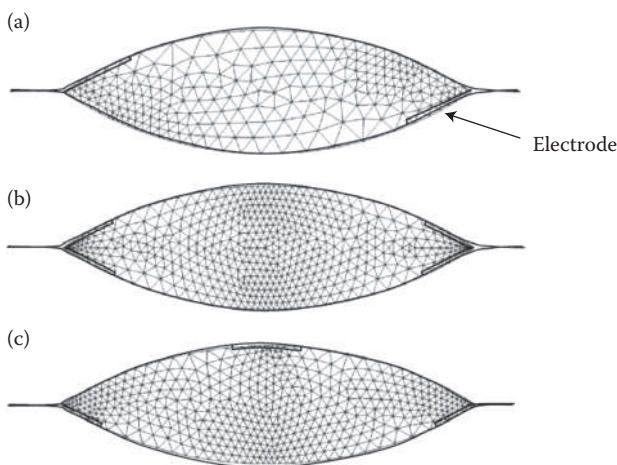


FIGURE 16.10 Different electrode configurations: pouches a, b, and c. (From Jun, S. and S. Sastry, *J. Food Process Eng.* 28, 417–436, 2005. With permission.)

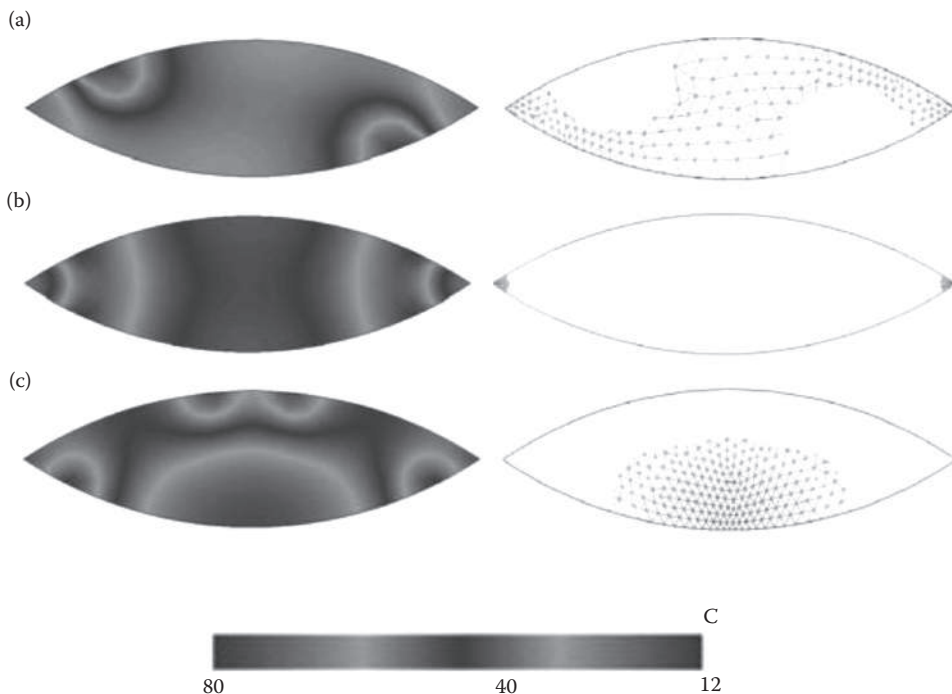


FIGURE 16.11 Simulated temperature distribution (left side) and cold zone (right side) of black beans in pouches a, b, and c after 300 s of heating. (From Jun, S. and S. Sastry, *J. Food Process Eng.* 28, 417–436, 2005. With permission.)

nodes) did not produce any noticeable change in the predicted medium temperature, but produced a small change in the particle cold-spot temperature. For the static model (LENC), increasing the number of elements from 616 elements (690 nodes) to 832 elements (952 nodes) yielded no changes in the medium temperature, but showed discernible changes in the particle cold-spot temperature by the end of the simulation period. A further increase in the numbers only yielded minor changes in the particle cold-spot temperature while significantly increasing the computing time (Salengke and Sastry, 2007a).

On the other hand, the iteration number required to achieve converged solutions depends on the convergence tolerance and the time step, and directly affects the computing time. The relatively large amount of time required by the LENC model was due to a requirement to solve the continuity equation for current over the whole domain of the mixture (Salengke and Sastry, 2007a).

16.2.4.6 Worst-Case Scenarios

The possibility of an under-processed particle is more difficult to monitor than the fluid temperature. It is clear that a variety of scenarios may occur during a process situation. Foods undergo various changes in their properties during processing including thinning, thickening, or gelation. Electrical conductivities are a strong function of the temperature, and it is possible that materials of low and high electrical conductivity may show reversed properties at another temperature. The potentially most dangerous occurrence is an undetected solid piece which passes through the system with insufficient heating. Such particles are of an electrical conductivity that is significantly different from the surroundings, but small enough to not distort the electric field to a detectable extent (Salengke and Sastry, 2007a).

It is therefore prudent for process specialists to investigate all potential scenarios in the process design. The worst cases appear to be scenarios wherein a single particle is of lower temperature than its surroundings. Several reported possible hypothetical worst-case situations are as follows:

1. *Involving an inclusion particle of lower electrical conductivity than its surroundings*; this situation has the potential for under-processing if the particle is either of small size relative to the heater cross section, or is aligned in such a manner as to present a minimal cross section to the electric field (Sastry and Salengke, 1998). Under these conditions, the major part of the current effectively bypasses the inclusion particle (CURRENT CHANELLING or BYPASS SCENARIO). The models suggest that the conductive heating in Ohmic conditions may be significantly different to conventional heating. In conventional heating, heat is transferred convectively through the fluid boundary layer and then by conduction into the particle. In Ohmic heating, the approach to thermal equilibrium may be enhanced by high heat generation around the edges of nonconducting particles. This heat generation arises from the high current flux in the fluid adjacent to the particle, since if the particle has a low conductivity, current flow is diverted around it (de Alwis and Fryer, 1990a). Similarly, the simulation results of Ye et al. (2003) show that when the potato particle has a lower electrical conductivity (0.037 S/m) than the fluid (1.3 S/m), there exists a high electrical density zone around the particle, consistent with their experimental MRI temperature observations. Ye et al. (2004) obtained good agreement between MRI temperature maps and model predictions for the system similar to Ye et al. (2003) (Figure 16.12).

The electrical current is diverted through the liquid, resulting in faster heating of the liquid phase, and the cold spot in the potato is located at the center (Ye et al., 2004). Some discrepancies between the MRI maps and model predictions are explained by the heterogeneous nature of the food materials resulting in a localized high heating zone, which is difficult to model, and the possibility of overestimating h_{fp} resulting in smoother transitions for model predictions (Figure 16.12).

The current bypass scenario is evident from modeling results showing considerably higher current densities within the medium at zones parallel to the cylindrical particle than within the particle (Salengke and Sastry, 2007a). The medium along the side of the particle is being heated faster than the medium in the front/back of the particles, which could lead to a significant difference between the two locations under the static condition. The use of the CAMF model is more appropriate than the LENC model. Especially if convection occurs, the LENC model will result in over-predicting solid temperatures. This scenario cannot be avoided by equipment design or product formulation since pumpable mixtures must, of necessity, consist of some particles that are small enough to form a relatively small cross section of the area in the path of the current. If any of these particles are of low electrical conductivity, the potential for under-processing exists. It is possible for such solids to escape detection prior to the heating process. The prevention of clogs in granular materials necessitates that the flowing solids have a maximum dimension approximately 1/3 of the diameter of the conveying tube.

2. *Involving an inclusion particle of higher electrical conductivity than its surroundings*; the greatest potential for under-processing is when the particle is aligned such as to present a significant fraction of the available cross section to the electric field. The major part of the current passes through the inclusion particle, but the electric field is weakened in its vicinity (Field Weakening Scenario) (Sastry and Salengke, 1998). A static situation is of greatest concern here since the fluid has more under-heated than overheated regions, consequently convection will tend to increase heating. The occurrence of a cold spot within the medium as predicted by the LENC model is attributable to the assumed absence of convective mixing. A static model provides more conservative predictions of the mixture cold-spot

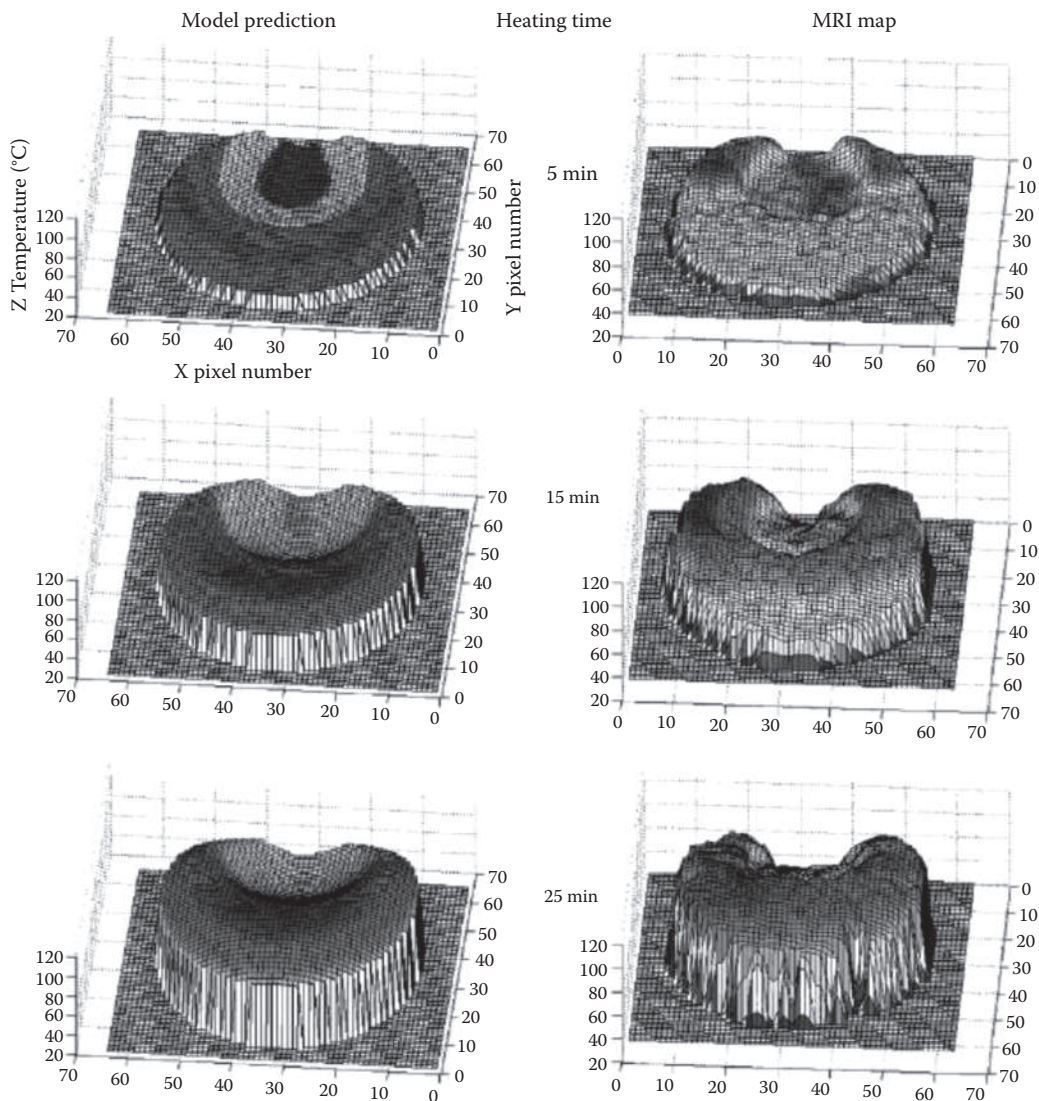


FIGURE 16.12 Model prediction vs. MRI map at middle cross section for the potato sample. (From Ye, X. et al., *Lebensm.-Wiss. u.-Technol.* 37, 49–58, 2004. With permission.)

temperature when the particle is more conductive than the medium (Salengke and Sastry, 2007a). This scenario requires the solid object to be of high electrical conductivity, and large enough to block most of the current path. Careful control of inlet particle size could help minimize any such occurrence. Even with alternative heater designs involving fields aligned across the flow, such a scenario could be controlled by restriction of particle size or inlet electrical conductivity (Sastry and Salengke, 1998).

3. *Involving a number of smaller highly conductive solids clumping together to cover a cross section of flow*; this situation can easily be avoided by on-line sensing of product electrical conductivity or the field weakening prior to the process (Sastry and Salengke, 1998). If a substantial disturbance is detected, the conductive section of the product could be diverted prior to heating. The LENC analysis would be conservative for this situation. The caution must be exercised in the choice of models for Ohmic heating (Sastry and Salengke, 1998).

Jun and Sastry (2005) reported that the pulsed Ohmic heating with high frequency and long delay time between pulses would effectively avoid a worst-case scenario, such as electrolytic gas production.

16.3 MODELING OF CONTINUOUS OHMIC SYSTEMS

In continuous processes, the product flows continuously throughout the heating, holding, and cooling sections. The expected advantages of a continuous process are an increase in production capacity, a reduction in power consumption, improved treatment homogeneity, and less damage to the food particles (Legrand et al., 2007).

Ohmic heating has shown considerable promise in producing high-quality sterile solid–liquid mixtures via continuous process. However, safety assurance is necessary before widespread use of this technology for sterilization of low-acid foods, which may support the growth of pathogenic spore forming bacteria. The fundamental problem in continuous flow sterilization of solid–liquid mixtures is our lack knowledge of temperature at the slowest heating location within the entire system (Salengke and Sastry, 2007a). Ohmic heating poses greater challenges in measurement than conventional heat exchange processes due to the presence of an electric field. The passage from a batch to continuous processing should satisfy numerous criteria (Figure 16.13): to produce a constant flow of a homogeneous suspension without blocking or mechanical degradation of particles, while operating over a range of concentrations or electrical conductivities (Legrand et al., 2007).

The development of a continuous flow Ohmic heater with improved electrode systems has opened new possibilities for industries interested in continuous sterilization of liquid–particle mixture. For purpose of commercial process design it is necessary to develop models for continuous heaters. The temperature measurement of particles in continuous flow Ohmic heating is even more difficult than under conventional heating because of the strong electrical field (Sastry, 1992). This necessitates the use of mathematical modeling to predict cold-spot temperatures; indeed modeling is a prerequisite to success in this process (Salengke and Sastry, 2007a). The flow characteristic of a continuous aseptic processing system makes the simulation of a two-phase system more difficult than a static system. The effect of viscosity, particle concentration, and interfacial heat-transfer coefficient of the suspending medium are crucial in predicting the heating effects for both liquid and solid phases in a continuous system (Fu and Hsieh, 1999).

Sastry (1992) modified the mathematical model, previously developed and verified for a static heater, to predict the temperatures of fluids and particles within a continuous heater with high particle concentrated suspensions. They discussed that since the static heater model has been tested against experiments, and continuous flow involved substituting a time scale with a length scale, the static model could be used with some confidence. The presence of large populations of low electrical conductivity particles results in slow heating of the entire mixture rather than a single phase alone. If the isolated low conductivity particles enter the system, the danger of under-processing exists; hence, the particle conductivity is a critical control point (Sastry, 1992).

A typical Ohmic heating column consists of various zones with electrodes spaced at intervals between them. The installation is composed of a cylindrical tube with electrodes in contact with the treated media in general (Benabderahmane and Pain, 2000). The potential difference imposed by these electrodes gives rise to a flow of electrical current inside the product. The resultant electrical field induces internal heat production by the Joule effect.

The heating of 3-D particles is first simulated, and then the fluid dynamics of the system is incorporated into the model, enabling the user to consider the flow patterns which are possible for various solid fractions and medium viscosities (de Alwis and Fryer, 1990a). The mathematical formulation involves interdependent electrical and thermal problems, the former is the voltage gradient (electrical field strength) and the latter involves determining liquid and particle temperature fields for the mixture flowing through the Ohmic column. The iterative solution process is initiated. For liquid

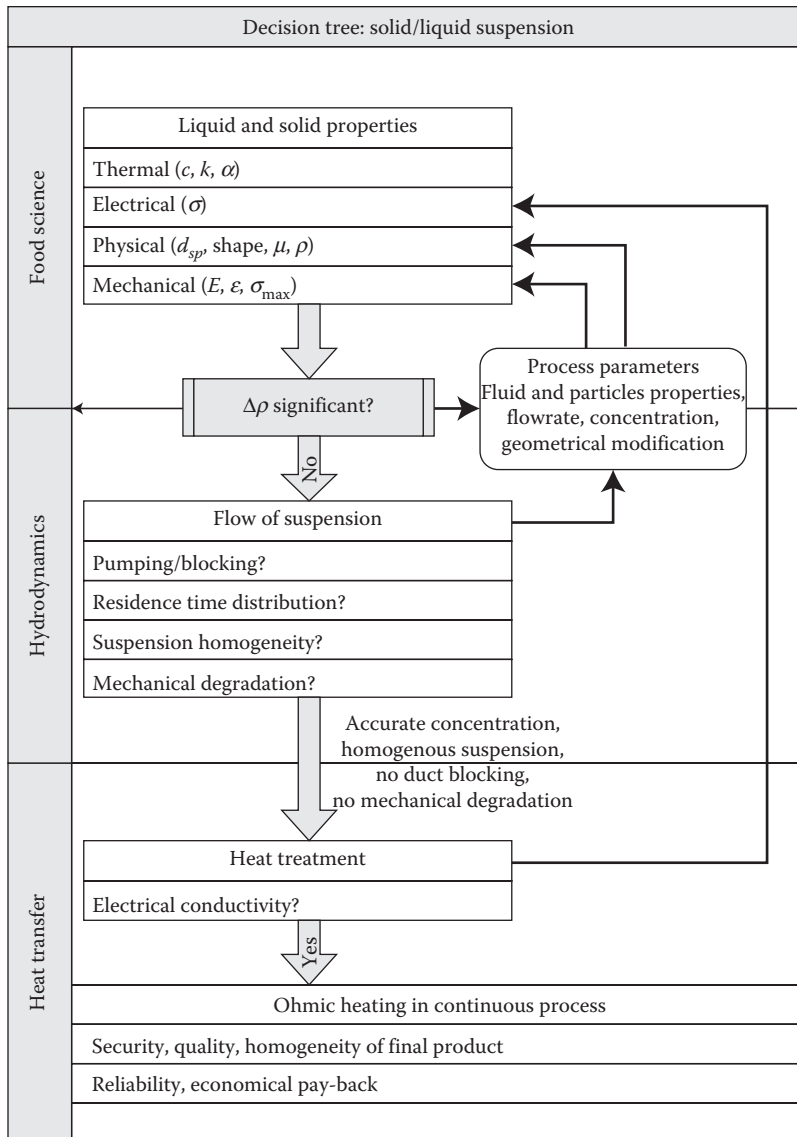


FIGURE 16.13 Passage from a batch to a continuous Ohmic heating process for complex solid–liquid food suspension–decision tree. (From Legrand, A. et al., *J. Food Eng.* 81, 447–458, 2007. With permission.)

temperature, the suitable initial assumptions regarding particle temperature and the voltage gradient are used. This is accomplished generally by a finite difference (i.e., Crank–Nicholson method) procedure in two dimensions (three dimensions are unnecessary due to the assumed symmetry of tubular flow). For the particle temperature, the same voltage gradient assumption and the fluid temperatures determined in the previous step are used. This may be accomplished by a three-dimensional finite element approach in space and finite differences in time (i.e., Galerkin–Crank–Nicholson approach). The computed fluid and particle temperatures are used to solve the electric field problem (i.e., using Galerkin finite elements). These computed voltages are reapplied to the solution of the thermal problems, and the entire process iterated until a convergent solution is obtained.

Particle residence times must be determined either by experiment or by assuming a velocity distribution; the former is probably a better method. Sastry (1992) presented a model where it was

assumed that plug flow existed through the heater, although the capability existed to simulate heat transfer to isolated fast moving particles. Since the process must be designed to sterilize the slowest heating particle, it must be assumed that it is possible for a particle to travel through the heater in its slowest heating orientation (de Alwis and Fryer, 1990b).

Results from the comparative modeling study suggest that for continuous flow, in Ohmic heating of solid–liquid mixtures, the mixed fluid model is more conservative when the cold spot is within the solid particle, but the static model is generally conservative when the cold spot is within the medium (Salengke and Sastry, 2007a).

16.3.1 VOLTAGE DISTRIBUTION

The electrical field distribution arises from the continuity equation for current (Equation 16.3), which must be solved over the domain of the mixture (Sastry, 1992).

16.3.1.1 Circuit Analogy Approach

A more expeditious approach is possible via circuit theory, where the Ohmic heater column is considered to be a set of equivalent resistances in a series (Sastry, 1992). This approximation is useful and realistic in that voltage gradients are likely to occur primarily along the length of the heater, and with high solid concentrations, plug flow is likely.

However, the analysis for a continuous heater is somewhat more involved because the product increases in temperature (and consequently conductivity) through the heater; thus, the voltage drop through each incremental section must be determined separately. For each incremental section i of thickness Δx lying between n and $n + 1$ (Figure 16.14); the resistance can be determined from that of a continuous (liquid) and a discontinuous (solid) phase, similar to Equation 16.5 in static heater, as follows (Sastry, 1992):

$$R_i = R_{ls,i} + \frac{R_{lp,i} R_{sp,i}}{R_{lp,i} + R_{sp,i}} \quad (16.74)$$

It is generally assumed that the area and the incremental section thickness of the discontinuous phase could be determined from the volume fraction of that phase ($V_{ls,i}$). If the electrical conductivities of liquid and solid are linear, they can be calculated from the temperature in the incremental section i (Equations 16.40 and 16.43) (Sastry, 1992). The total resistance of the Ohmic heater column is then;

$$R = \sum_{i=1}^N R_i \quad (16.75)$$

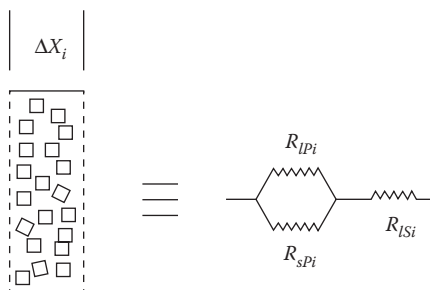


FIGURE 16.14 Equivalent circuit for an incremental section. (From Sastry, S.K., *J. Food Process Eng.* 15, 263–278, 1992. With permission.)

The total current passing through the system is

$$I = \frac{\Delta V}{R} \quad (16.76)$$

The voltage distribution can be calculated assuming all equi-potential zones are approximately planar and perpendicular to tube walls (a reasonable approximation when the phases are uniformly mixed). Thus, the voltage drop over increment i is calculated as $\Delta V_i = I R_i$ (Sastry, 1992). The solution of this problem requires that temperatures of continuous and discontinuous phases be known throughout the heater length to determine the current I from which to calculate voltage gradient. The computational effort required for iterative refinement is therefore considerable. It can be decreased by improving the initial estimate of voltage drops by the following procedure (Sastry, 1992);

- If there is a reasonable uniformity in temperature of phases, the lumped analysis for the particle temperature could be assumed.
- The voltage gradients are calculated iteratively with results of lumped system analysis until convergence is obtained.
- The resulting voltage gradient is used as the first estimate when thermal and electrical problems are solved frequently in their entirety.

16.3.1.2 Local Heat-Generation Approach

When an electrical potential is applied to a material having electrical conductivity, σ , the potential field is obtained by applying Laplace's law (Equation 16.4). The electrical field E created generates a heat power per unit volume G inside the material (Benabderrahmane and Pain, 2000);

$$G = \sigma E^2 \quad (16.77)$$

For a solid–liquid mixture, where the two phases have different conductivities, Equation 16.100 is valid only locally, and is dependent on the local arrangement of the particles and their actual volume fractions (Benabderrahmane and Pain, 2000). In the case of a zero solid volume fraction, solid is not present in the mixture. The heat power generation per unit volume is as follows:

$$G_{l0} = s_l E_{l0}^2 \quad (16.78)$$

The numerical study of Zhang and Fryer (1993b) enabled the characterization of the evolution of the volume-weighted heat generation in the two phases as a function of the mean electrical generation in the liquid without particles (\bar{G}_{l0}), the local particle/liquid conductivity ratio, and the local solid volume fraction (Benabderrahmane and Pain, 2000). The mean electrical generation in the liquid and solid phases, \bar{G}_l and \bar{G}_p , respectively, are expressed in terms of the heat generation ratio functions R_{Gl} and R_{Gp} (Benabderrahmane and Pain, 2000);

$$\bar{G}_l = R_{Gl} \bar{G}_{l0} \quad (16.79)$$

$$\bar{G}_p = R_{Gp} \bar{G}_{p0} \quad (16.80)$$

The calculation of the local heat generation for a centered cubic system of particles subjected to an electric field normal to two of the six planes of the system leads to the functions, R_{Gl} and R_{Gp} , which have the same form as R_G (Benabderrahmane and Pain, 2000);

TABLE 16.2
Component Functions of the Heat Generation Ratios for Ohmic Heating Column

	Liquid Expression	ε^2	Particles Expression	ε^2
f_1	$\frac{1 - 1.31f_{\text{act}}}{1 + 0.81f_{\text{act}} - 0.61f_{\text{act}}^2}$	0.9999	0	—
f_2	$1 - 1.16f_{\text{act}} - 2.01f_{\text{act}}^2 + 4.01f_{\text{act}}^3$	0.9993	$2.25 - 2.19f_{\text{act}} + 1.17f_{\text{act}}^2$	0.9998
f_3	$4.75f_{\text{act}} - 30.08f_{\text{act}}^2 + 88.35f_{\text{act}}^3 - 120.71f_{\text{act}}^4 + 62.31f_{\text{act}}^5$	0.9988	0	—
f_4	$1 - 0.75f_{\text{act}} - 2.70f_{\text{act}}^2 + 4.13f_{\text{act}}^3$	0.9992	$\frac{1}{1 + 0.93f_{\text{act}} + 3.67f_{\text{act}}^2}$	0.9997
f_5	$f_1 + f_2 + f_3 - 1 - f_4$	—	$\frac{0.24 - 0.40f_{\text{act}}}{1 + 3.40f_{\text{act}} - 3.46f_{\text{act}}^2}$	0.9987

Source: From Benabderrahmane, Y. and J.P. Pain, *Chem. Eng. Sci.* 55, 1371–1384, 2000. With permission.

$$R_G = \frac{f_1 + f_2 \mathbf{s}_R + f_3 \mathbf{s}_R^2}{1 + f_4 \mathbf{s}_R + f_5 \mathbf{s}_R^2} \quad (16.81)$$

The components f_1, f_2, f_3, f_4 , and f_5 are functions of the actual volume fraction ϕ_{act} ($0 \leq \phi_{\text{act}} \leq 0.68$), and are given for each phase with the corresponding correlation coefficients in Table 16.2. σ_R is the local particle–liquid electrical conductivity ratio ($\mathbf{s}_p^* / \mathbf{s}_l^*$). Starting from the hypothesis of a uniform electrical field in the tube cross section, the potential field computation can be done supposing a no-flux condition at the wall and constant electrical current density J (Muller et al., 1993; Benabderrahmane and Pain, 2000). Laplace’s law can be applied in the one-dimensional space over the entire domain with electrode potential values as boundary conditions.

16.3.2 VELOCITY DISTRIBUTION

It involves simultaneous solution of the equations of fluid motion as well as the linear and angular momentum equations for fluid and the particles in the mixture. For vertical Ohmic column, the momentum equation for the vertical velocity v , in cylindrical coordinates, is (Quarini, 1995)

$$\mathbf{r} \left(\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial r} + v \frac{\partial v}{\partial z} \right) = - \frac{\partial P}{\partial z} + g(\mathbf{r} - \mathbf{r}_0) + \frac{1}{r} \frac{\partial}{\partial r} \left(\mathbf{m} r \frac{\partial v}{\partial r} \right) + \frac{\partial}{\partial z} \left(\mathbf{m} \frac{\partial v}{\partial z} \right) \quad (16.82)$$

where $u = 0$ and v is a function of radial position only. To simplify, it is necessary to make reasonable assumptions regarding the fluid flow field. For assumptions such as—the radial and azimuthal flow velocities are zero; the center of the pipe is a point of symmetry; zero velocity at the wall; the thermodynamic and transport properties are independent of temperature—Equation 16.82 simplifies them for steady state (Quarini, 1995);

$$0 = - \frac{\partial P}{\partial z} + g(\mathbf{r} - \mathbf{r}_0) + \frac{1}{r} \frac{\partial}{\partial r} \left(\mathbf{m} r \frac{\partial v}{\partial r} \right) \quad (16.83)$$

at the center of the pipe ($r=0$), symmetry condition $\partial v/\partial r=0$, and at the pipe wall ($r=R_0$), the no-slip condition on solid surfaces $v=0$. For the mixtures in an Ohmic column, in many instances it is assumed that a homogeneous flow occurs where particles and fluid move at similar average velocities, although local fluid velocities may deviate considerably from the average value to yield significant fluid–particle relative velocities. The velocity of the mixture is then calculated assuming that it behaves as a composite non-Newtonian fluid, and its velocity distribution can be characterized as

$$v_z(r) = v_{\text{mean}} \left(\frac{3N+1}{N+1} \right) \left[1 - \left(\frac{r}{R} \right)^{N+1/N} \right] \quad (16.84)$$

Another approach regarding a mass balance of the mixture flow and the differences in the mean residence times of the two phases could be used. This difference is often expressed in terms of a *mean slip velocity* (Benabderrahmane and Pain, 2000). In the plug flow, the higher the volume fraction the smaller the standard deviation of the particle residence time distribution (Benabderrahmane and Pain, 2000). The mass flow rates of mixture (\dot{m}_m), particle (\dot{m}_p), and liquid (\dot{m}_l) are dependent on each phase velocity and volume fraction. The expression of v_p and v_l , the particle and liquid velocities, respectively, and of the actual solid volume fraction (ϕ_{act}) are given by (Benabderrahmane and Pain, 2000);

$$v_p = \frac{1}{2} \left[(v_m - v_{\text{slip}}) + \sqrt{(v_m - v_{\text{slip}})^2 + 4\mathbf{f}_{\text{del}} v_m v_{\text{slip}}} \right] \quad (16.85)$$

$$v_l = \frac{1}{2} \left[(v_m + v_{\text{slip}}) + \sqrt{(v_m + v_{\text{slip}})^2 - 4(1 - \mathbf{f}_{\text{del}}) v_m v_{\text{slip}}} \right] \quad (16.86)$$

$$\mathbf{f}_{\text{act}} = \frac{1}{2v_{\text{slip}}} \left[(v_{\text{slip}} - v_m) + \sqrt{(v_m - v_{\text{slip}})^2 + 4\mathbf{f}_{\text{del}} v_m v_{\text{slip}}} \right] \quad (16.87)$$

where $v_{\text{slip}} = v_l - v_p$ is the slip velocity and ϕ_{del} is the delivery volume fraction of the particles. In the solution of energy and mass equations for the mixture in the continuous flow Ohmic heater, dimensionless form of the velocities (v_m^* , v_p^* , and v_l^*) are written by using the following relation:

$$v^* = \frac{v}{v_m} \quad (16.88)$$

To predict the particle trajectories in the liquid phase, the Lagrangian approach can be used. In this approach, the influence of particles on the flow field of the continuous phase is considered by the momentum transfer of each particle (Unluturk and Arastoopour, 2003). The momentum transfer from the dispersed phase to the continuous phase is obtained by computing the change in the momentum when an individual particle passes through each control volume. Equation 16.89 represents the equilibrium between inertia, drag, gravity, and other forces exerted on the particle per unit mass of particle (Unluturk and Arastoopour, 2003).

$$\sum \bar{F} = \bar{F}_A + \bar{F}_B + \bar{F}_D + \bar{F}_G + \bar{F}_P + \bar{F}_S + \bar{F}_M = \frac{d\bar{v}_p}{dt} \quad (16.89)$$

where $\overline{F_A}$, $\overline{F_B}$, $\overline{F_D}$, $\overline{F_G}$, $\overline{F_P}$, $\overline{F_S}$, and $\overline{F_M}$ are the virtual mass force, Basset history force, drag force, gravity, force due to pressure gradient, Saffman lift force, and Magnus lift force, respectively (Unluturk and Arastoopour, 2003). Saffman lift force is due to the pressure distribution developed on a particle because of rotation induced by a velocity gradient while Magnus lift force is due to the particle rotation that may be caused by sources other than the velocity gradient; particle–particle collisions and particle–wall impact. For particle rotation, the angular velocity of the particle can be calculated by angular momentum equation. If the particle is spherical the equation of rotation becomes:

$$T = -I \frac{d\vec{\omega}_p}{dt}$$

where

$$I = \frac{2}{5} m_p \left(\frac{D}{2} \right)^2 \quad (16.90)$$

I is the moment of inertia of the sphere and T is the torque acting on the sphere (Unluturk and Arastoopour, 2003). Dennis et al. (1980) derived the equation of the torque required to rotate the sphere with uniform angular velocity in a fluid at rest. For the cases of using Saffman or Magnus forces in simulations, Unluturk and Arastoopour (2003) compared the agreement of model solutions to experimental data of Lareo et al. (1997) (Figure 16.15). Figure 16.15a shows that particles lag behind the fluid flow at the outlet in all radial locations. However, the simulation in this case (Figure 16.15a) predicts the presence of particles near the wall. It is explained by absence of the Saffman lift force considered, which causes particles to migrate toward the center of the pipe, and the particle–wall effect (Unluturk and Arastoopour, 2003). Since the density of the particles is very close to the liquid phase, particles follow the parabolic liquid phase velocity profile with a small slip velocity. The inclusion of the Magnus lift force into the simulation of particle flow behavior has no significant effect (Figure 16.15b). In the case of Saffman force and particle slip boundary condition (particle axial velocity on the wall) incorporated into the simulation (Figure 16.15c), a particle free region is seen near the wall and more particles are transported toward the center of the pipe, which was observed experimentally by Lareo et al. (1997). The average particle residence time was reported as 4.25 s while the fastest particle had been found to travel much slower than the one predicted based on laminar flow assumption without considering the effect of particles on the liquid flow (Unluturk and Arastoopour, 2003).

Eliot-Goderéaux et al. (2001) defined the “passage time” term rather than classical “residence time” term. They discussed that all particles are required to spend the same amount of time in the heating and holding parts of the Ohmic processing installation. In continuous processes, passage time of liquid and solid phases of foodstuff in the different sections of equipment depends on the kind of flow (capsule, concentric, saltation, etc.) and may fluctuate, thus leading to great variations in the final product quality (Eliot-Goderéaux et al., 2001). Residence time distribution (RTD) can be described by E (exit age distribution of RTD) or F (cumulative RTD function) functions through the introduction of tracer particles at the entrance of the system either in a pulse or step mode, and then enumerating them at the exit end (Eliot-Goderéaux et al., 2001). The E curve, which gives the normalized output concentration (E) with respect to time, is given by (Eliot-Goderéaux et al., 2001)

$$E(t) = \frac{C}{\int_0^\infty C dt} \quad (16.91)$$

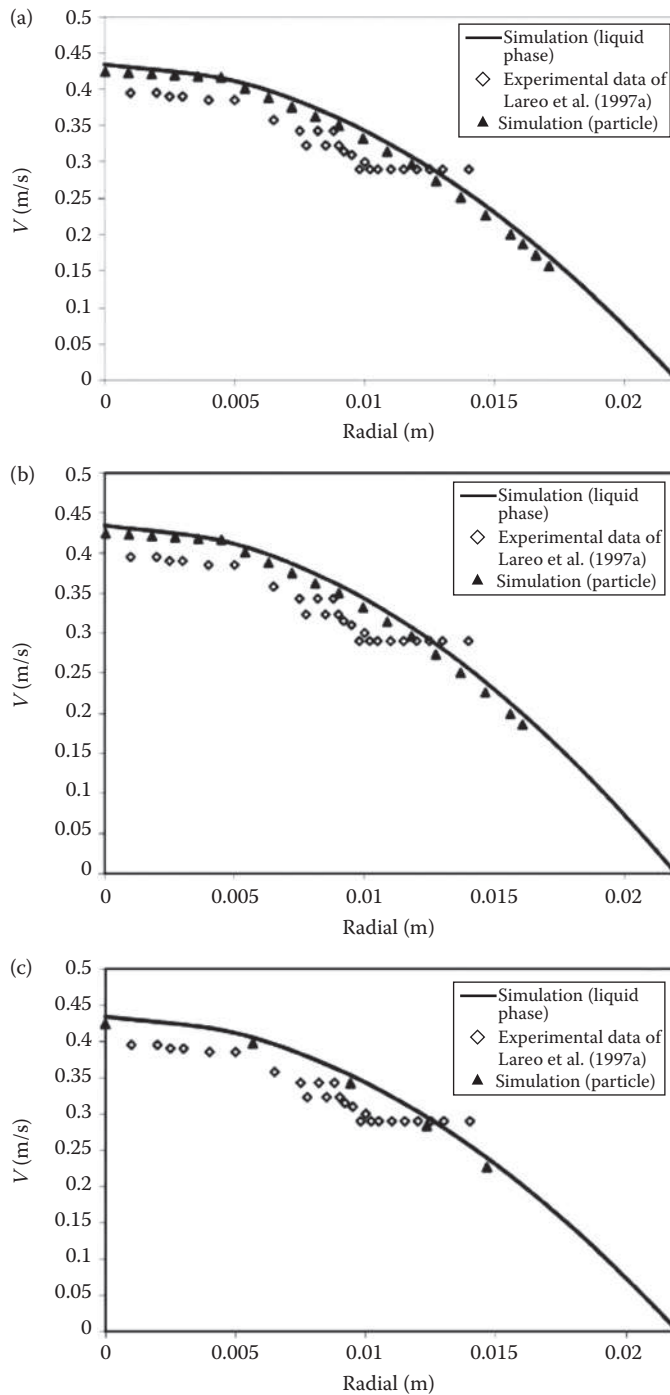


FIGURE 16.15 Velocity profiles of the liquid phase and particles at the outlet of the vertical pipe (0.3% CMC, $D_p = 9.3$ mm, $\rho_p = 1034$ kg/m³) considering (a) only gravity and drag forces, (b) the particle–wall collision, the angular velocity of the particles, Magnus force, plus features of (a), (c) Saffman lift force with a particle slip boundary condition, plus features of (a). (From Unluturk, S.K. and H. Arastoopour, *Ind. Eng. Chem. Res.* 42, 3845–3850, 2003. With permission.)

where C is the tracer concentration. The F function, which represents the accumulation of particles at the exit with a residence time t or less is given by

$$F(t) = \int_0^{\infty} E(t) dt \quad (16.92)$$

Careful attention must be paid to the methods of injection and detection used. Two types of injection detection exist (Eliot-Goderéaux et al., 2001);

1. Flux where the tracer concentration is directly proportional to the velocity field.
2. Planar where the tracer concentration is constant across the pipe cross section.

While the maximum and minimum passage times remain constant, the value of the mean passage time is a function of the injection and detection methods used (Eliot-Goderéaux et al., 2001). If the solid concentration is not constant, passage time distribution (PTD) is used rather than RTD term. The Hall effect sensor can be used to perform passage time measurements on continuous Ohmic processing system. It uses the Hall principle, which is a semi-conductor material supplied with a constant current that produces an output voltage when a transverse magnetic field is applied (Eliot-Goderéaux et al., 2001). Passage time is the time difference measured for a tracer passing between two Hall effect sensors. Tracers can be fabricated with a magnet and any plastic materials to have properties as close to the food particles as possible.

16.3.3 TEMPERATURE DISTRIBUTION

The present models in literature generally assumed that plug flow existed through the heater. This assumption needed to be verified for individual instances, but was realistic for suspensions of the high solids concentration situations considered (Sastry, 1992). The thermal problem involves separate energy balances on liquid and particles in the mixture flowing through Ohmic column. For the liquid within any incremental section of thickness Δx , between locations n and $n + 1$, the following energy balance is used:

$$\mathbf{r}_f v_z C_{pf} \frac{\partial T_f}{\partial z} = \nabla(k_f \nabla T_f) + \dot{u}_f + n_p h_{fp} A_p [T_{p,s} - T_f] \quad (16.93)$$

where v_z is the velocity of the mixture in the axial direction of the tube and \dot{u} is the volumetric heat generation. The volume of the fluid in the incremental section is as follows (Sastry, 1992);

$$V_f = \frac{\pi}{4} d^2 \Delta x V_{f,f} \quad (16.94)$$

$V_{f,f}$ is the volume fraction of the fluid in the incremental section of the column. The boundary conditions can be taken as:

- B.C.1. At entrance of the column $T_f|_{z=0} = T_{f,ini}$
- B.C.2. At the walls, heat is lost from the fluid to the outside air; $k_f \nabla T_f \cdot \vec{n}|_w = U(T_w - T_{amb})$

The liquid temperature at each successive incremental location ($n + 1$) can be determined from Equation 16.116, if the voltage field (V distribution) and the mean particle surface temperature ($T_{p,s}$) are known. For the particles, the conduction heat-transfer equation with temperature-dependent

internal heat generation is similar to Equation 16.49. The time-dependent boundary condition and the energy generation term for the particle can be predicted by Equations 16.50 and 16.51, respectively.

Mathematical models for the effective electrical conductivity of the mixture based on the assumption that if the solids are evenly distributed throughout, the fluid in the continuous Ohmic heater could be used. The isotropic Kopelman model could be used, especially if the particles in the mixture are cubic (Palaniappan and Sastry, 1991):

$$s_e = \frac{s_f(1-c)}{1-c\left(1-V_{f,p}^{1/3}\right)} \quad (16.95)$$

where $V_{f,p}$ is the volume fraction of the solid and the c deals with the ratio of the conductivities of particles and fluid (Palaniappan and Sastry, 1991). If the tube walls are insulated, the boundary condition here is given by:

$$\nabla V|_w = 0 \quad (16.96)$$

at the entrances and exits:

$$V|_{\text{ent}} = V_1 \quad V|_{\text{exit}} = V_2 \quad (16.97)$$

Sastry (1992) discussed that the model developed for predicting solid and liquid phase temperature was in agreement with the gathered experimental data. Some under-predictions noted were explained by results of assumptions regarding liquid-to-particle convective heat-transfer coefficients. Solving the energy equations for liquid and solid phases in dimensionless form, two important quantities of ΔT_{ref} and E_{est} are expressed. Benabderrahmane and Pain (2000) considered the special case of a single-phase flow of the carrier fluid (zero solid volume fraction) at constant electrical conductivity, moving at a mean velocity v_m . They described the system that the liquid enters the tube at the reference temperature T_m , and exits the tube at the reference temperature difference T_{ref} . The reference temperature difference is as follows:

$$\Delta T_{\text{ref}} = T_{\text{ref}} - T_m \quad (16.98)$$

E_{est} is an estimation of the electrical field needed to obtain an increase in the liquid temperature equal to the reference temperature difference ΔT_{ref} :

$$E_{\text{est}} = \left(\frac{(\mathbf{r}Cp)_l \Delta T_{\text{ref}} v_m}{L S_{\text{ref}}} \right)^{1/2} \quad (16.99)$$

Benabderrahmane and Pain (2000) expressed a source term (S) in energy equations of liquid and solid phases. This term represented the heat exchanges of the considered phase with the external media and the local internal heat generation by electrical energy:

$$\frac{D}{Dt}(\mathbf{r}CpT) = \nabla(k\nabla T) - T \left(\frac{\partial P}{\partial T} \right)_r \nabla v + S \quad (16.100)$$

Equation 16.100 is applied for both liquid and solid phases. The liquid heat source term corresponds to the sum of the heat powers electrically generated or exchanged with the external media (wall, particles). For a liquid volume element of length ∂z with an internal generation G_l and a local solid volume fraction $(1 - \phi_{\text{act}})$ corresponding to a particle specific area a (Benabderrahmane and Pain, 2000), heat powers are expressed as

$$\partial \dot{q}_g = (1 - \mathbf{f}_{\text{act}}) \left(\frac{\mathbf{p} D_t^2 \partial z}{4} \right) G_l \quad (16.101)$$

$$\partial \dot{q}_w = (\mathbf{p} D_t \partial z) h_w (T_w - T_l) \quad (16.102)$$

$$\partial \dot{q}_p = a \left(\frac{\mathbf{p} D_t^2 \partial z}{4} \right) h_p (T_l - T_p) \quad (16.103)$$

where D_t is the tube diameter, $\partial \dot{q}_g$ is the power generated internally by Joule effect, $\partial \dot{q}_w$ is the power exchanged with the wall at a temperature T_w with respect to a convection coefficient h_w and $\partial \dot{q}_p$ is the power corresponding to convective transfers with particles in respect to exchange coefficient h_p . When the liquid thermal field is one dimensional in space, the corresponding local internal generation equals its cross-sectional volume-weighted mean value, \bar{G}_l (Benabderrahmane and Pain, 2000). The source term could be written as

$$S_l = \frac{\partial \dot{q}_g + \partial \dot{q}_w - \partial \dot{q}_p}{\partial V_l} = (1 - \mathbf{f}_{\text{act}}) \bar{G}_l + a h_p (T_p - T_l) \quad (16.104)$$

When the interparticle and the particle-wall heat transfers are neglected for solid phase, the heat source term in the particles is only composed of the internal electrical generation, which is the volume mean generation over the whole particle (Benabderrahmane and Pain, 2000).

To solve the energy equations, dimensionless forms can be used (Zaror et al., 1993; Benabderrahmane and Pain, 2000);

$$T^* = \frac{T - T_m}{\Delta T_{\text{ref}}} \quad t^* = t \frac{v_m}{D_t} \quad v^* = \frac{v}{v_m} \quad x^* = \frac{x}{D_t} \quad G^* = \frac{G}{\mathbf{s}_{\text{ref}} E_{\text{est}}^2} \quad (16.105)$$

where x represents the existing directions in the system (namely z and r) and v_m is the mixture inlet velocity. Following Reynolds, Nusselt, Prandtl, and Biot, dimensionless groups are used in the solution of energy balances for solid and liquid phases:

$$Re_m = \frac{\mathbf{r}_l v_m D_t}{\mathbf{m}} \quad Re_p = \frac{\mathbf{r}_l v_{\text{slip}} D_p}{\mathbf{m}} \quad Nu_p = \frac{h_p D_p}{k_l} \quad Pr = \frac{\mathbf{m} C p_l}{k_l} \quad Bi = \frac{h_p D_p}{2k_p} \quad (16.106)$$

The dimensionless forms of the energy balance for solid and liquid phases are given in Equations 16.107 and 16.108, respectively:

$$v_l^* \frac{\partial T_l^*}{\partial z^*} = Re_m^{-1} Pr^{-1} \frac{\partial^2 T_l^*}{\partial z^{*2}} + S_l^* \quad (16.107)$$

$$\frac{\partial T_p^*}{\partial t^*} = Re_m^{-1} Pr^{-1} \left(\frac{k}{r Cp} \right)_p \left(\frac{k}{r Cp} \right)_l^{-1} \left[\frac{1}{r^{*2}} \frac{\partial}{\partial r^*} \left(r^{*2} \frac{\partial T_p^*}{\partial r^*} \right) \right] + S_p^* \quad (16.108)$$

The dimensionless form of the source terms for liquid and solid phases can be written as

$$S_l^* = (1 - f_{\text{act}}) \bar{G}_l^* L^{*-1} + Nu_p Re_m^{-1} Pr^{-1} \frac{a}{D_p^*} (T_p^* - T_l^*) \quad (16.109)$$

$$S_p^* = \bar{G}_p^* L^{*-1} \quad (16.110)$$

where

$$\frac{\partial}{\partial z^*} \left(\mathbf{s}_l^* \frac{\partial U^*}{\partial z^*} \right) = 0 \quad (16.111)$$

for dimensionless electric potential U^* (Benabderrahmane and Pain, 2000). The boundary conditions for the liquid and particle thermal field are

$$T_l^*(0) = 0 \quad \left. \frac{\partial T_p^*}{\partial r^*} \right|_0 = 0 \quad (16.112)$$

$$\left. \frac{\partial T_l^*}{\partial z^*} \right|_{l^*} = 0 \quad \left. \frac{\partial T_p^*}{\partial r^*} \right|_{D_p^*/2} = \frac{2Bi}{D_p^*} (T_l^* - T_{ps}^*) \quad (16.113)$$

T_{ps}^* is the dimensionless temperature of the surface of the particle. The initial conditions for each time step Δt^* are $T_p^*(z^*, r^*, 0) = 0$ and $T_p^*(z^*, r^*, t^* + \Delta t^*) = T_p^*(z^* - \Delta z^*, r^*, t^*)$. Benabderrahmane and Pain (2000) solved these equations by using a finite volume method with the line-by-line Gauss–Siedel method coupled with the Tridiagonal Matrix Algorithm, while they used Gauss–Siedel method for the electrical field resolution. To validate their model and numerical procedure applied, they studied the assessment of the agreement with an analytically resolvable case; zero particle volume fraction situation. They discussed that the thermal responses correlated closely, confirming the adequacy of the numerical procedure, with a maximum relative error of less than 1%.

Zaror et al. (1993) reported that the overall rate is controlled by the interphase heat-transfer process under small Bi ($Bi < 1$ for small particles) and a low conductivity solid case. A simple model can be formulated as temperature gradients within the particle are negligible (Legrand et al., 2007). The governing equations reduce to a pair of lumped differential equations and can be solved numerically by any of the usual methods (the Runge–Kutta or Euler method, etc.) to calculate the solid and liquid temperature histories and the required residence time in the heater (Legrand et al., 2007).

16.3.4 FACTORS AFFECTING TEMPERATURE DISTRIBUTION IN CONTINUOUS OHMIC SYSTEMS

Legrand et al. (2007) reported that major factors influencing particle velocity in a stream of carrier fluids are: viscosity, relative density (particle to fluid), relative size (particle to tube), particle shape, and concentration of the solid phase in the fluid. They suggested that it is essential to have

a perfect knowledge of the physical, mechanical, thermal, and electrical properties of the particles and the carrier fluid to develop continuous thermal processing. The maximal concentration and mechanical degradation of particles, duct plugging, heterogeneity in generated heat and heat transfer, widespread of sterilization or cooking efficiencies are limiting factors, which must be identified to control the properties of the product.

16.3.4.1 Electrical Conductivity Changes

It is important to characterize the range of variation of electrical conductivity for the components of the product. Thermal process calculation must be based on the lowest conductivity particle in the mixture. Since most mixtures will consist of a range of particle conductivities, it becomes necessary to identify lower limits of these values (Sastry, 1992).

For fixed slip velocity, delivery volume fraction and diameter ratio, the solid could be more heated than the liquid at the tube outlet in the cases of both equal conductivities and lower conductivity solids (Benabderrahmane and Pain, 2000). However, the heat exchange does not yet display any stabilization when reaching the tube outlet. The increase in electrical properties of liquid comparing to the particle induces a liquid domination in the beginning of the process, which is accomplished by a particle center colder than the particle surface.

Zaror et al. (1993) investigated the effect of electrical conductivity on the temperature distribution of a solid–liquid mixture in continuous Ohmic sterilizer. They discovered that the solid temperature rises faster than the liquid temperature independent on the Biot number; sterilization is almost complete at the heater outlet when the electrical conductivity of the solid is higher than the liquid. They concluded that the overheating within the solid could be observed at very low Bi . On the other hand, the particle temperature at the heater outlet decreases sharply with further decreases in the Biot number when the liquid electrical conductivity is higher than that of the solid and, hence, no sterilization occurs in the heater itself (Legrand et al., 2007).

16.3.4.2 Particle Shape and Volume Ratio

Food particles are often large with a diameter of the same order of magnitude as the pipe, nearly buoyant, irregular in shape, formed with a range of surface and mechanical properties. Their presence induces important hydrodynamic perturbations (Benabderrahmane and Pain, 2000; Legrand et al., 2007). High solid volume fractions increase the interparticle and particle–wall interactions.

A particle in a shear flow experience hydrodynamic forces that will tend to make it rotate; this in turn will “stir” the fluid, and promote mixing (Quarini, 1995). The propensity of the particles to cause stirring depends on the velocity gradients in the column and their shape; for example, a perfect sphere causes less stirring than an irregular shape of the same volume. In general, particles enhance mixing and thus reduce temperature peaking in specific zones of the flow channel (Quarini, 1995).

Since the rigorous simulation of such systems is scientifically difficult and come at a very high cost, many authors assumed that the mixture behavior at high volume fractions approaches the plug flow (Muller et al., 1993, 1994; Zaror et al., 1993; Quarini, 1995; Benabderrahmane and Pain, 2000). Mankad et al. (1995) presented that the dispersed and carrying phase residence times needed for a complete sterilization in a plug flow were very sensitive to both the slip velocity and the thermal properties.

For a fixed slip velocity, diameter ratio, and identical electrical conductivities, the solid could be hotter than the liquid in the mixture flowing through the Ohmic column (Figure 16.16a). On the other hand, the temperature difference between the two phases decreases with an increasing solid volume fraction. If the solid volume fraction and the slip velocity are kept constant at $\phi_{\text{del}} = 30\%$ and $v_{\text{slip}}^* = 25\%$ and the electrical conductivities of both phases are identical, the liquid heating is less efficient as the particle diameter increases (Benabderrahmane and Pain, 2000). Since larger particles have a higher specific area and induce a higher convective heat exchange, they also exhibit a higher inertia in the heat conduction and the energy generated in the particle center requires a larger time to be transferred to the liquid.

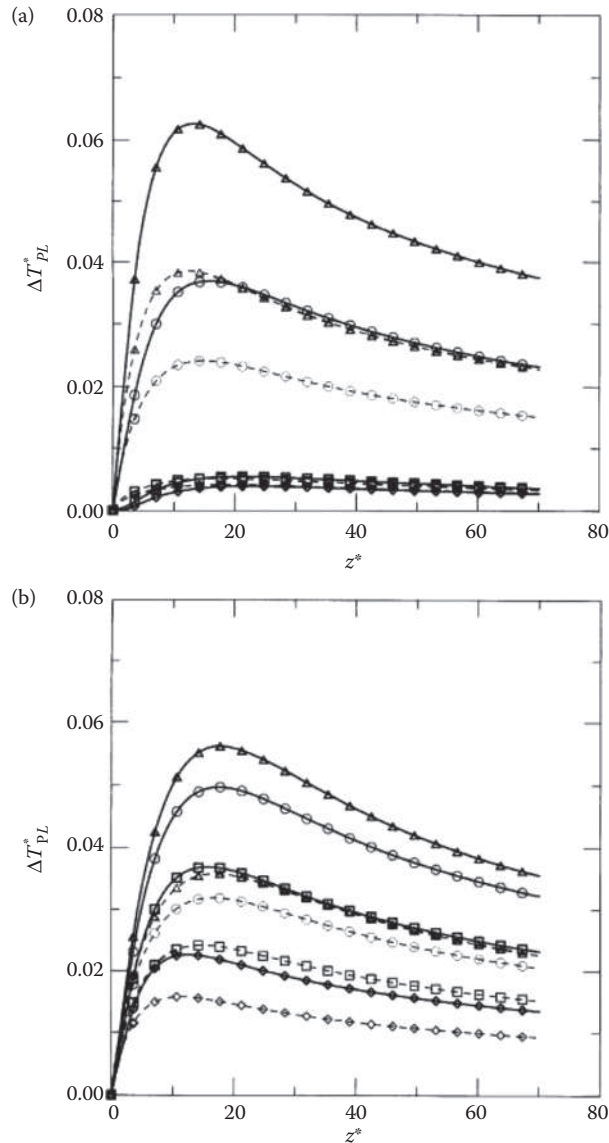


FIGURE 16.16 Particle-liquid temperature difference (a) for different delivery volume fractions (\diamond) $\phi_{del} = 55\%$, (\square) $\phi_{del} = 30\%$, (\circ) $\phi_{del} = 10\%$, (Δ) $\phi_{del} = 1\%$; (—) center; (—) surface and (b) for different slip velocities (\diamond) $v_{slip}^* = 0\%$, (\square) $v_{slip}^* = 1\%$, (\circ) $v_{slip}^* = 25\%$, (Δ) $v_{slip}^* = 50\%$. (From Benabderrahmane, Y. and J.P. Pain, *Chem. Eng. Sci.* 55, 1371–1384, 2000. With permission.)

Based on the findings in static Ohmic heaters, particles heat slowly when oriented in a manner permitting maximum current bypass (e.g., long-thin particles of low electrical conductivities are oriented parallel to the current) (Sastry, 1992). The model predictions show that changing the aspect ratio (diameter-to-length ratio) greatly affected fluid temperature by changing the surface area in contact with the fluid phase. Eliot-Goderéaux et al. (2001) discussed that the mean passage time did not change significantly with increasing concentrations of particles and increasing flow rates. On the other hand, the presence of bends and obstacles (enlargements or reductions) can cause the breaking of large food particles and involve blockage of the Ohmic column (Legrand et al., 2007). In order to keep the particle whole, a low solid concentration is required although this could be far from

economic reality. In addition, at a low solid concentration, the density differences between each phase can be sufficient to cause a severe suspension heterogeneity, which will contribute to the mechanical damage of the food particles (Legrand et al., 2007). Particle dimensions and volume increases during the process must be taken into account in determining the maximum packing volume fraction in continuous Ohmic treatment in order to avoid duct blocking and mechanical degradation.

16.3.4.3 Flow Properties

The flow characteristics of viscous food flow in aseptic processes lay between two extremes; in one case, a plug flow exists where all food spend the same time in the aseptic processes and receive the same thermal treatment. In other extreme, a laminar Newtonian flow can exist, where the maximum fluid velocity at the centre of the pipe is twice the average velocity (Eliot-Goderéaux et al., 2001). The fastest particles only receive half the thermal treatment of the average solid/liquid mixture.

Sastry and Palaniappan (1992a) reported that the particles moving at velocities equal to the average fluid velocities tended to heat slightly faster than the fluid. This occurred even if the particles were less conductive than the fluid. Fast moving particles will thermally lag the fluid, as expected; however, the effect is not as great as with conventionally heated foods. For continuous-flow heating with significant velocity profiles, the model must be capable of describing the radial variation in temperatures due to radial velocity variation. If such a velocity exists, the material at the center heats slowly because of its low residence time, while the material at the tube wall heats more rapidly.

Poiseuille flow heating lead to a strongly flattened velocity profile that is initially parabolic at the tube inlet and the assumption of uniform electrical field in the tube cross section caused only weak errors (Benabderrahmane and Pain, 2000). Muller et al. (1994) showed the presence of an instability caused by a mixed convection phenomenon generating a periodic fluctuation of the longitudinal centerline velocity. They also discussed that the thermal field exhibited an analogous oscillating behavior. The mixed convection effects could cause recirculating flows and affect the product residence time.

Tucker and Withers (1994) performed a series of trials on the holding tube of an Ohmic heating pilot plant using diced vegetables in starch solutions and found that plug flow was approached as the solid concentration increased (Eliot-Goderéaux et al., 2001). Benabderrahmane and Pain (2000) found that the particles flowing through the Ohmic column could display a temperature greater than that of the liquid having identical electrical conductivities (Figure 16.16b). In the no-slip case, the surface of the particle is slightly hotter than the particle center due to very weak convection. The medium and high slip velocities lead to a hotter particle center from the beginning to the end of the tube. It is the effect of the particle residence time, which is higher than that of the liquid. Thus, the particles are exposed to the electrical field for much longer times. As the slip velocity increases the convective heat exchange with the liquid increases. Further in the tube, the temperature evolution experiences an asymptotic stabilization.

Eliot-Goderéaux et al. (2007) determined PTD in the Ohmic heating column for cubic and bead particles. They reported that a cubic geometry of particles resulted in a more heterogeneous distribution of passage times and food particles flowed slower than liquid through heating sections. They explained the reason that the geometry around the electrodes may create dead zones is because the channeling of particles near the pipe center is being disturbed by the presence of electrodes. It has been obtained that the fastest particle spent at least 60% more time in the heating section than the liquid phase.

The extended passage time of solids in the Ohmic column can result in considerable damage to the product (Eliot-Goderéaux et al., 2001). The differences between both phases render these parameters a critical control point in the process and question the problem of product sterility vs. product quality. The product may be overcooked or not sterilized if the minimum passage time could not be adjusted properly. Particles spending more time in the column can heat higher than fluid, and cause problems in the holding section of the Ohmic sterilizer (Eliot-Goderéaux et al., 2001).

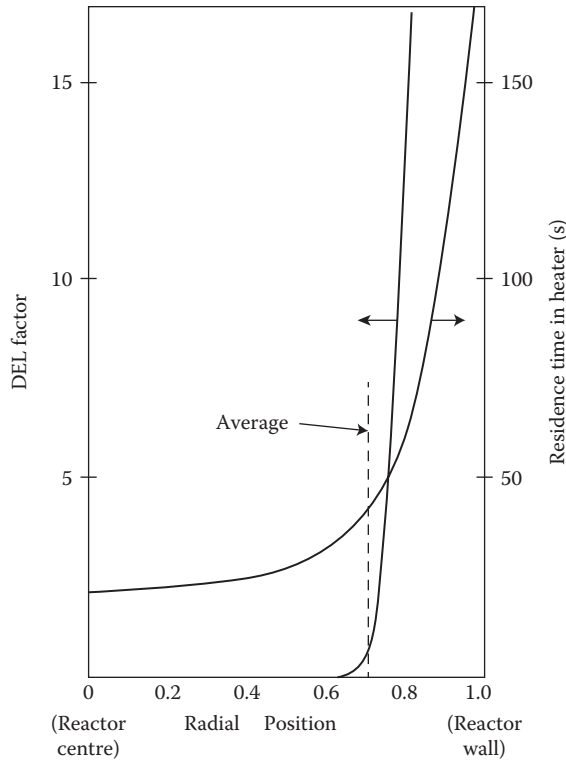


FIGURE 16.17 The effect of velocity radial profile: residence time in heater and Del factor at outlet, as a function of heater radial position. (From Zaror, C.A., D.L. Pyle, and G. Molnar, *J. Food Eng.* 19, 33–53, 1993. With permission.)

Figure 16.17 shows the residence time in the heater and *Del* factor (Equation 16.114) at the outlet of the heater as a function of heater radial position for laminar flow conditions (Zaror et al., 1993).

$$Del = \nabla = - \int_{n_0}^n n^{-1} dn = \int_0^t A e^{\left(\frac{-E}{RT}\right)} dt \quad (16.114)$$

where n is the number of viable organisms or spores in the control volume. The model results of Zaror et al. (1993) shows that particles near the wall will be completely sterilized by the time they leave the heater whereas those near the center of the Ohmic column will remain unsterilized (Figure 16.17). Thus, laminar flow conditions could give rise to radial temperature gradients, which could lead to under heating in the heater center and overheating near the walls, and may necessitate process cooling and proper design of the holding section (Zaror et al., 1993).

16.3.4.4 Viscosity and Density

The rheological behavior of the carrier fluid affects the particle residence time and a high-viscosity affords some degree of protection to the particle, but also influences the velocity profiles in the continuous system (Legrand et al., 2007). If the fluid surrounding the particle is not highly viscous (similar to water) natural convection effects are sufficient to smooth out nonuniformities in heating (Sastry and Palaniappan, 1992a). Under these conditions the static Ohmic heater may reasonably represent the continuous flow situation. If the fluid is viscous enough to suppress natural convection, nonuniformities may occur. On the other hand, if the fluid viscosity is increased while maintaining

the electrical conductivity constant, the overall heating rate of both phases increases. This appears to be analogous to the “RUNAWAY” heating effects observed for microwave heating. This is a beneficial effect since continuous flow Ohmic heating requires viscous fluid carriers to prevent phase separation. These effects need further quantification.

The relative density (particle to fluid) is an important factor to characterize the heterogeneity of a flowing suspension (decantation, flotation), since density differences between solids and fluids may be sufficient to generate particle settling (Liu et al., 1993). This consequently results in different sterilization and cooking efficiencies between solid and liquid phases and among the solid phases.

16.3.4.5 System Properties

For the case of low heating rates and adiabatic walls, the flow distribution is parabolic for laminar flow whereas the temperature distribution is flat across the whole flow area (Quarini, 1995). As the volumetric heating rate is increased, both the flow and temperatures begin to change. The temperature is flat in the central zone, rising rapidly at the wall, thus the highest temperature occurs at the wall. The velocity distribution becomes flatter in the central zone then rises to a peak before dropping to zero at the walls. Depending on the modified Grashoff number $Gr_m = g\beta r^2(\Delta T R_0)R_0^3/\Delta z m^2$, the velocity profile was obtained to show a peak before the center of the pipe (Quarini, 1995).

The Ohmic system could consist of cooling on the outside of the walls and, thus, may give a more uniform temperature profile (Quarini, 1995). The exact degree of cooling has a profound influence on the velocity and temperature profiles produced. A small degree of cooling lowers the temperature of the fluid adjacent to the wall without affecting the velocity distribution too much (Quarini, 1995). With sufficient cooling the temperature of the fluid can be lowered to a level where the buoyancy forces are reversed and are of sufficient magnitude to cause a flow reversal close to the wall (Figure 16.18). The simulation for a different case of heat conduction

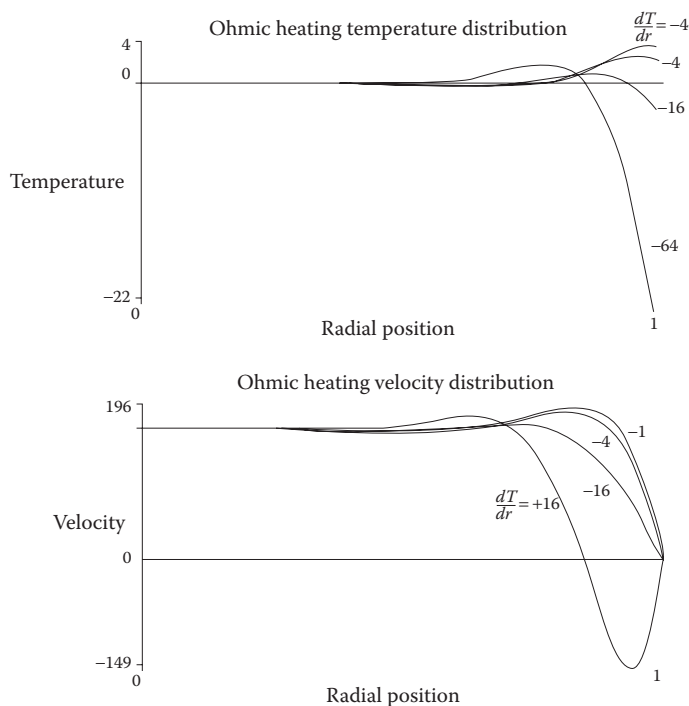


FIGURE 16.18 Temperature and velocity distributions across the channel showing the effects of cooling on the wall of the Ohmic heating column ($Pr = 0.61$, $dT/dr = -1, -4, -16, -64, -256$, $Gr = 7000$). (From Quarini, G.L., *J. Food Eng.* 24, 561–574, 1995. With permission.)

through the column walls may be useful in assisting the designer to identify where the controlling thermal resistances are, and to estimate how much heat could be sensibly transferred through the walls. Quarini (1995) suggested that food scientists and equipment designers must work together to achieve a more uniform temperature distribution; the food scientist should attempt to generate heat (i.e., by designing foods having a strong negative conductivity–temperature coefficient) which will minimize the temperature peaking in regions of low flow, while the equipment designer should look at ways of removing heat from regions where the temperature tends to peak, and ways of hydrodynamically ensuring that most uniform velocity distribution exists in the vertical duct.

16.3.4.6 Worst-Case Scenarios

The worst-case scenario during continuous Ohmic heating would be one involving an isolated low conductivity particle located in the highest conductivity environment consistent with that product, being oriented with a minimal cross-sectional area exposed to the current (Sastry, 1992). This particle would obviously experience an even greater thermal lag if its residence time were shorter than the average.

From the processors' standpoint, the best way to operate would be to control the range of particle electrical conductivities to the maximum extent possible; use as high a concentration of particles as possible. This could prevent situations such as isolated low conductivity particle existing in a high conductivity environment. Precooking treatments and careful product formulation could be used to achieve the desired effect (Sastry, 1992).

Benabderrahmane and Pain (2000) concluded that the particle temperature at the column outlet could be greater than the liquid temperature, which is impossible in the traditional thermal processes. It was presented that the process critical point was, unlike in traditional processes, situated in the liquid and not in the particle for a mixture with homogeneous electrical conductivity. They discussed the influence of the inhomogeneous electrical conductivities on the heating history and hence sterilization efficiency.

Passage time of heterogeneous foods has to be well known and controlled to obtain a homogeneous quality. The microbiological safety of the product can be assured by taking the measured temperature of the fluid at the exit of the Ohmic column and the shortest passage time of particles at the desired particle concentration and flow rate as process parameters (Zaror et al., 1993; Eliot-Goderéaux et al., 2001). Any heterogeneity in the suspension (capsule flow or settling) generates nonuniformity in the delivery of the electric field and in the heating rate (Legrand et al., 2007). In the worst case, the suspension heterogeneity leads to instability of electrical parameters. The relative conductivity of the mixture at different particle concentrations and the flow behavior of the suspension will be determinant in the decision as to whether the Ohmic heater can be considered as a relevant technology or not (Legrand et al., 2007).

Further modeling efforts are needed on different flow types, different components of mixtures, and nonuniform-shaped particles in continuous Ohmic systems.

16.4 CONCLUDING REMARKS

The procedure in the mathematical modeling of the Ohmic heating process for static and continuous systems is similar to obtaining temperature and voltage distributions. In continuous systems, the velocity distribution is an additional procedure affecting other distributions. Solving the models requires definite assumptions. To assess the effects of assumptions on the predicted results, measurement experiments can be used for verification. Several factors affecting the temperature and velocity distributions are especially important for multiphase flows (liquid–solid mixtures). Model predictions regarding worst-case scenarios in Ohmic heaters are useful in designing and implementing efficient Ohmic heating systems that produce high-quality sterile solid–liquid mixtures.

NOMENCLATURE

A	Area (m^2)
a	Particle specific area (m^2)
ac	Alternating current
B_1, B_2, B_3	Temperature coefficients of electrical conductivity
Bi	Biot number (dimensionless)
c	Constant
C	Parameter describing quality loss (min) or tracer concentration in Equation 16.114
C_1, C_2, C_3	Constants for electrical conductivity–temperature relations
$Conc$	Concentration
C_p	Specific heat at constant pressure (J/kg K)
D	Diameter of the heater (m)
d	Diameter of the particle (m) or characteristic dimension
E	Electric field strength (V/m) or parameter describing the loss of enzyme activity (min) or normalized output concentration with respect to time in Equation 16.114
E	Energy (J)
E_2	Concentration coefficient of electrical conductivity
El	Electrical characteristic number (dimensionless)
\overline{F}	Force (N)
F	Lethality (min) or function representing the accumulation of particles with time t in Equation 16.115
f_1, f_2, f_3, f_4, f_5	Functions
F_j	Load vector
F_p	Required lethality (min)
g	Acceleration due to gravity (m/s^2)
\overline{G}	Mean electrical generation (W/m^3)
G	Heat power inside the material per unit volume (W/m^3)
Gr	Grashoff number (dimensionless)
h_f	Convective heat-transfer coefficient ($\text{W/m}^2 \text{K}$)
I	Current (A) or moment of inertia in Equation 16.113
J	Current density vector (A/m^2)
K	Consistency coefficient (Pa s^n)
k	Thermal conductivity (W/mK)
k^*	Enhanced thermal conductivity (W/mK)
K_c	Cell constant ($1/\text{m}$)
K_{ij}	Stiffness matrix
L	Distance between two parallel electrodes (m)
l	Length (m)
\dot{m}	Flow rate (kg/s)
m	Exponent or temperature coefficient of electrical conductivity
M	Mass (kg)
M_{ij}	Mass or capacitance matrix
N	Flow behavior index (dimensionless)
\vec{n}	Unit normal vector
n	Number
nPT	Normalized passage time
Nu	Nusselt number (dimensionless)
\dot{Q}	Heat power (W)
\dot{Q}	Heat-transfer rate (W)

P	Pressure (Pa)
Pr	Prandtl number (dimensionless)
PT	Passage time
Q	Energy (J)
r	Coordinate dimension
R	Resistance (ohm)
R_0	Radius of column (m)
Ra	Rayleigh number (dimensionless)
Re	Reynolds number (dimensionless)
R_G	Heat-generation ratio function
rms	Root mean square
S	Source term
SPC	System performance coefficient (dimensionless)
T	Temperature (°C) or torque (N m) in Equation 16.113
t	Time (s)
t^*	Dimensionless time
\dot{u}	Internal heat generation per unit volume (W/m ³)
U	Overall heat-transfer coefficient (W/m ² K)
U^*	Dimensionless electric potential
V	Potential difference (V)
v	Velocity (m/s)
V	Volume (m ³)
V_f	Volume fraction
w	Angular frequency (1/s)
x	Coordinate dimension
y	Coordinate dimension
z	Coordinate dimension or temperature dependency of the lethality (K)

GREEK LETTERS AND OTHER SYMBOLS

σ	Electrical conductivity (S/m)
σ_R	Local particle–liquid electrical conductivity ratio
ρ	Density (kg/m ³)
∇	Gradient
Δ	Increment
ε^2	Square root of correlation coefficient
ε_r	Relative permittivity
ε_0	Absolute permittivity
τ	Relaxation time
θ	Coordinate dimension
ϕ	Basis function
ϕ_F	Fractional sterility
ϕ_C	Fractional quality loss
ϕ_E	Fractional enzyme loss
ϕ_{act}	Actual volume fraction
ϕ_{del}	Delivery volume fraction
δ_{ij}	Kronecker delta function
β	Coefficient of thermal expansion (1/K)
α	Thermal diffusivity (m ² /s)
μ	Viscosity (Pa s)

SUBSCRIPTS AND SUPERSCRIPTS

c	Charge or conduction when used with current density or convective when used with heat-transfer rate
d	Displacement
f	Fluid
l	Liquid
s	Solid or surface when used with temperature
p	Particle
P	Parallel
S	Series
j	Node number index
i	Node number index
eff	Effective
n	Step index
N	Step index
0	Reference or initial value
r	Relative
N_2, N_3	Exponent
amb	Ambient
m	Mean
w	At wall or heater when used with area
∞	Bulk
h	Heater
ref	Reference
max	Maximum
min	Minimum
ini	Initial
ent	Entrance
exit	Exit
est	Estimated
t	Tube
g	Generated
*	Dimensionless

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17 Sensitivity Analysis of the Ohmic Heating Process

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17.1 INTRODUCTION

Process sensitivity analysis is one of the important steps for successful process development, since it can provide basic knowledge of how the variation in the output of the process can be apportioned, qualitatively or quantitatively, to different sources of variation in the processing conditions. Ohmic heating, also called electrical resistance heating, is an advanced thermal processing method wherein the food material, which serves as an electrical resistor, is heated by passing electricity through it. Compared with conventional heating methods, Ohmic heating has obvious advantages in shortening the heating time and improving the processed-food quality especially for processing foods containing large particulates, but it is more challenging to design and develop an Ohmic heating method, based on a thermal process dealing with multi-phase foods which have different thermal, physical, and electrical properties. For the Ohmic heating used for multiphase foods, the heating rate of each phase depends not only on the electrical field strength applied and electrical conductivity, but is also affected by the electrical conductivity of other phases, and heat transfer between phases due to the temperature difference between them during the process. In order to develop a reasonable thermal sterilization process, which can maximize the food quality and meet the minimum requirement of food safety for preservation and consumption, it is necessary to determine the coldest spot, identify the critical process variables, and build up acceptable process deviations to be used for on-line monitoring and control. This chapter focuses on the review of research work relating to sensitivity analysis of Ohmic heating

processes, including electrical conductivity, particle size, shape, and concentration, viscosity of liquid, production formulation, and an example of sensitivity analysis for a continuous Ohmic heating system.

17.2 THE EFFECTS OF ELECTRICAL CONDUCTIVITIES

Ohmic heating rates are critically dependent on the electrical conductivity of the food being processed. Key considerations in the electrical conductivity include overall conductivity, its difference between carrier fluid and particles and nonconductive materials.

17.2.1 OVERALL ELECTRICAL CONDUCTIVITY

de Alwis and Fryer (1992) provided details on the effects of electrical conductivity on the Ohmic heating process. For a given Ohmic heating system, in order to achieve the desired heat rate (normally in the region of 1–5°C/s), the amount of electrical power (P) required can be estimated using the product flow rate (m), specific heat capacity (C_p), and density (ρ) together with the in and out temperatures:

$$P = m \rho C_p (T_{\text{out}} - T_{\text{in}}) \quad (17.1)$$

The current (I) and voltage (V) required to deliver that power can then be found using standard electrical relationships:

$$\begin{aligned} I &= \sqrt{\frac{P}{R}} \\ V &= \sqrt{PR} \end{aligned} \quad (17.2)$$

where R is the overall system resistance. There is a limitation for voltage and current that can be applied to a given commercial system. The maximum safe current will depend on the current density which the system can sustain, a function of both electrode and system geometry. Stirling (1987) gives 8000 A/m² as a safe maximum current density for the combination of electrode and electrolytes applied in Ohmic food processing, and further suggests a permitted maximum current density of 4000 A/m² to allow for variations in the electrolyte type and concentration. The maximum voltage which can be sustained in a commercial system will be limited by the cost of electrical and control hardware.

These limitations will restrict the range of conductivities for which Ohmic heating is possible. In the limits of very low electrical conductivity, the resistance of the food will be so high that it will be impossible to get a satisfactory heating rate using the highest possible voltage. In the limit of very high electrical conductivity, in contrast, the current will be over the limit that the system can sustain. Therefore, for a given Ohmic heating system, prior to processing the conductivities of food materials should be tested to make sure that they are in the acceptable range.

17.2.2 CONDUCTIVITY DIFFERENCE BETWEEN CARRIER FLUID AND PARTICLES

For processing heterogeneous food mixtures of liquid and particles, the conductivity difference between carrier fluid and particles is the key parameter affecting the heating behavior of both liquid and particles during Ohmic heating. A solid immersed in a liquid can either heat faster or slower than the liquid. This effect has been found to be a function of both solid and liquid electrical conductivity and the orientation of the particles to the electric field (de Alwis et al., 1989). The mixture of liquid and particles can be described by three types of electrical circuits as shown in Figure 17.1a–c. If particles and liquid are connected in a series type (Figure 17.1a), then a higher conductivity part will heat slower. In other words, if their connection is parallel as in Figure 17.1b, then the higher conductivity will heat faster. Figure 17.1c shows a circuit model with a combination of parallel and of series, which is suitable for most real cases and has been successfully used for modeling of the

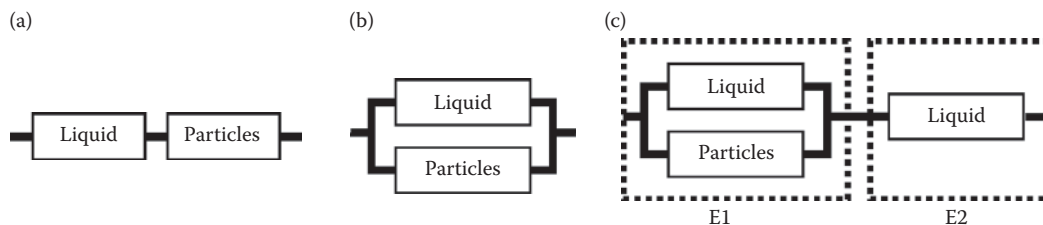


FIGURE 17.1 Electrical circuit simulators for mixtures of liquid and particles. (a) Series; (b) parallel; (c) combination of series and parallel.

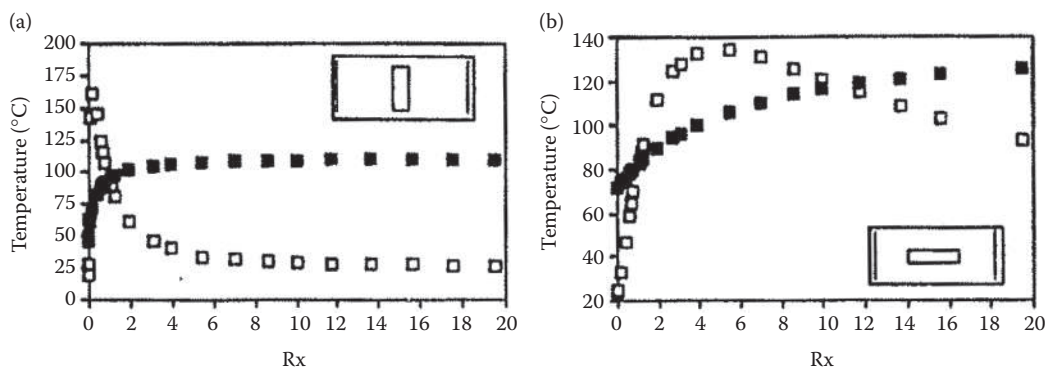


FIGURE 17.2 Temperature versus Rx plots during Ohmic heating with varying solid conductivity (a) particle perpendicular to applied field, (b) for particle parallel to applied field (■, solid; □, liquid).

Ohmic heating process for multiphase foods (Sastry, 1992). de Alwis and Fryer (1992) conducted a series of simulations to examine solid and liquid heating rates in the two principle orientations, where the particle is parallel and perpendicular to the field, over a wide range of solid electrical conductivity. The results are shown in Figure 17.2a and b, where Rx is the ratio of solid conductivity to liquid conductivity. When the particle is perpendicular to the field, in Figure 17.2a, the solid temperature decreases with Rx. However, when the particle is parallel to the field (Figure 17.2b), the solid temperature increases with Rx. This means that the heating behavior of particles will be dependent on not only the conductivity themselves but also particle size and shape.

17.2.3 NONCONDUCTIVITY MATERIALS

Nonconductivity materials such as fats, oils, nuts, air, alcohols, bones, and ice should be minimized. These nonconducting materials will not be heated by electrical resistance. In addition, localized overheating can occur in conducting regions near the exterior of the nonconducting materials. Consequently, large portions of these nonconducting materials can have deleterious effects on the evenness of product heating and should, therefore, be minimized through careful selection of raw materials (Zoltai and Swearingen, 1996).

17.3 THE EFFECTS OF PARTICLE SIZE AND CONCENTRATION

Various combinations of meats, vegetables, pasta, and fruits can be successfully processed when accompanied by an appropriate carrier medium and suitable process controls. Basically, there are three fundamental particulate considerations including size, shape, and concentration. Optimizing the correct combination of these characteristics will result in an excellent texture through uniformity of particulate heating.

As mentioned previously, one of obvious advantages to using Ohmic heating is its capability to process large particulate foods, which are difficult for a conventional heating method. Technically, for an Ohmic heating process, the particulate size should be determined by the pipe diameter and aseptic filler capability in the particulate size. But actually, the consumer response suggests that particulates larger than 1 in³ would require cutting prior to consuming and thereby reduces convenience. Thus, the 1 in³ is usually considered as the limit size for the Ohmic heating process (Zoltai and Swearingen, 1996). In addition, if particulates have significantly lower electrical conductivity than the carrier medium, the former will be heated slower than the latter during Ohmic heating. As particulates increase in size, surface to volume ratios decrease; hence, the heat transfer between particulates and the carrier medium is affected. This phenomenon is presented in detail in the following section about sensitivity analysis of continuous Ohmic heating process.

For the continuous Ohmic heating process, the plug flow is the desired type, as it can create a uniform residence time for products to pass through the pipes. In order to have this result, the foods with a formulation of high concentration particulates are commonly used for the Ohmic heating process. Particulate concentration in most Ohmic formulations ranges from 20% to 70%. Extremely low or high concentrations require special consideration of size, shape, and texture to optimize stability of the formulation during processing. Higher concentrations can be processed if the particulates are pliable and small, and their geometry is varied, as this decreases the voids between particles. Lower concentrations generally require a higher-viscosity carrier medium to maintain particulate suspension.

17.4 THE EFFECTS OF CARRIER MEDIUM VISCOSITY

The main function of the carrier fluid is to hold the particulates in a suspended state throughout the entire process. Usually, low viscosity carrier fluids can be used for products containing a high concentration of particulates, while high viscosity carrier fluids should be used for those with low particulate concentration. If the viscosity is inadequate, or if significant thinning occurs during processing, particulates may settle and/or carrier fluid may flow past the particulates without suspending them. This will result in substantial unevenness of heating. On the other side, if the carrier fluid is highly viscous, particulate abrasion can cause an effect in textural integrity and significant system backpressure problems may also occur. Changes in viscosity during processing, such as starch gelatinization or release of moisture from particulates, can also result in unevenness of heating. Therefore, in practical applications, it is important that the starch solution be pre-gelatinized to avoid the phase changes during processing.

The effects of fluid viscosities on the Ohmic heating rates of fluid–particle mixtures were investigated by Khalaf and Sastry (1996). They used fluids of identical electrical conductivities having different viscosities with a fixed amount of solid particles (of electrical conductivity lower than the fluid) and heated them Ohmically in batches (static and vibrating) and continuous flow heaters. In the static Ohmic heater, the heating rate of the fluid and particles was found to be comparable for the different fluids. However, in the vibrating Ohmic heater, the heating rate of fluid and particles was found to increase with increasing fluid viscosity. In the continuous flow Ohmic heater, the mixture with the higher viscosity fluid, heated faster than that with the lower viscosity fluid. The important implication is that poor inter-phase convective heat transfer may actually contribute to accelerated overall heating, since the more (electrically) conductive phase does not lose heat readily to the less (electrically) conductive phase, and consequently heats rapidly, transferring heat to the other phase by larger temperature differences.

17.5 HEATING BEHAVIORS OF SOLID–LIQUID MIXTURES UNDER WORST-CASE HEATING SCENARIOS

Sterilization of solid–liquid by Ohmic heating requires the assurance that all parts of the mixture are processed adequately to meet the minimum lethality target value. It is a challenging task to

identify the cold spot for Ohmic heating to be applied for processing of multiphase foods with different electrical conductivity values. Various modeling and experimental works have been performed to understand the heating behaviors of solid–liquid mixtures under Ohmic heating conditions (de Alwis and Fryer, 1990; Orange et al., 1998; Sastry, 1992; Sastry and Palaniappan, 1992; Sastry and Salengke, 1998). Salengke and Sastry (2007) reported the Ohmic heating behaviors of solid–liquid mixtures under two processing conditions: one involving a static medium surrounding the solid; and the other involving a mixed fluid. Two worst-case heating scenarios were investigated: (1) where the particle is less conductive than the medium (medium-more-conductive) and (2) where the particle was more conductive than the medium (particle-more-conductive). The results from modeling and experiments showed that for medium-more-conductive cases, the temperature of the inclusion particle significantly lagged that of the medium. Hence, heating rates of the inclusion particle differ significantly, lagged than that of the medium. Heating rates of the inclusion particle were faster under the static than under the mixed (agitated) condition, suggesting that a more conservative result occurred under the agitated condition. For the particle-more-conductive cases, the temperature of the particle led that of the medium, indicating that the mixture's cold spot was in the medium. In experiments involving a small particle (particle to the tube ratio of 0.1), the worst-case heating was observed under the mixed condition. When a large particle (area ratio of 0.2) was involved, the worst-case heating occurred under the static condition.

17.6 SENSITIVITY ANALYSIS OF THE CONTINUOUS OHMIC HEATING SYSTEM

The above experimental investigation results are useful for understanding effects of various major factors on the heating behaviors of liquid and particles being processed. However, for a real processing system, there are more processing variables to be considered in terms of product safety and quality. The process sensitivity analysis of a real continuous Ohmic heating system for soup products containing large particulates was performed by Chen et al. (2010) by the use of a valid computer modeling package. The system being investigated included three sections: heating, holding, and cooling. The heating section consisted of two electrical heaters, between which there was an intermediate holding tube to equalize the temperature difference between different phases after the first heater. The Ohmic processing system dimensions are listed in Table 17.1. The major processing variables selected for sensitivity analysis included conductivities of both particle (σ_p) and liquid (σ_f); surface heat-transfer coefficient of particles, size of particle (S_p), particle concentration (P_c), flow rate (V_f), and initial temperature (T_i). The base and deviation levels of each variable are listed in Table 17.2. The base conditions were selected from a sample product. Response variables used for sensitivity analysis were: the carrier fluid temperature at the end of holding tube (TL), particle center temperatures (TP1 and TP2) at the entrance and end of the holding tube, and accumulated lethality values of carrier fluid (FL), particle center (Fo), and particle integrated (Fv) at the end of the holding tube. The process temperature for the carrier fluid at the entrance of the holding tube was fixed at 133°C. This means that no matter how much other variables change such as conductivity, initial temperature, and flow rate, the process temperature at the end of the holding tube is always kept at the 133°C. This objective is automatically controlled in the real Ohmic heating system, but in the computer model it was performed by manually adjusting the voltages in each heating section.

17.6.1 ELECTRICAL CONDUCTIVITIES OF CARRIER FLUID AND PARTICLES

Figure 17.3 illustrates the effect of the carrier fluid conductivity (σ_f) on the heating behavior and accumulated lethality values of carrier fluid and particles. It can be seen that with the increase of σ_f , the carrier fluid temperature and particle temperatures at the end of holding tube were decreased under a given process temperature of 133°C. For example, when σ_f increased 10% from the base condition, the carrier fluid temperature decreased from 130.3°C to 129.6°C at the end of holding tube, and the particle temperature at the entrance of the holding tube was changed from 128.4°C to

TABLE 17.1
Ohmic Aseptic Processing System Dimensions

Sections	Length (m)	Internal Diameter (m)
First heater	2.76	0.062
Intermediate holder	14.96	0.064
Second heater	3.96	0.062
Second holder	14.37	0.064
Cooler	51	0.064

TABLE 17.2
Major Processing Variables and Deviation Ranges

	σ_f^a (S/m)	σ_p^a (S/m)	D_p (m ² /s $\times 10^{-7}$)	h_{fp} (W/°C/m ²)	S_p (mm)	P_c (%)	V_f (L/h)	T_i (°C)
−20%	1.424	0.96	1.16	112	16	52	1600	56
−10%	1.602	1.08	1.30	126	18	58.5	1800	63
Base	1.605	1.11	1.45	140	20	65	2000	70
10%	1.958	1.32	1.59	154	22	71.5	2200	77
20%	2.136	1.44	1.74	168	24	78	2400	84

^a Electrical conductivity at 70°C. Temperature coefficients for the electrical conductivities are 0.0142 and 0.0104 for liquid and particles, respectively.

126.6°C. A similar trend can be found for the particle temperature at the end of the holding tube. The reduction of carrier fluid temperature at the end of holding tube can be attributed to the lower particle temperature at the entrance of the holding, absorbing more heat from carrier fluid during the holding time. Since the process temperature for the carrier fluid at the entrance of the holding tube is fixed at the same temperature of 133°C as mentioned above, the increase of σ_f resulted in the system automatically reducing the power level (voltage), the heating rate for the particles with same conductivity thus decreased during the heating section, causing lower temperature at end of heating tube (or entrance of the holding tube).

The change of the accumulated Fo value corresponded to the temperature results. With the increase of σ_p , the F value for both carrier fluid and particles were reduced. This meant that increasing σ_f would result in the lower F value for both carrier fluid and particles. On other hand, if comparing the ratio of Fo/Fv, it can be found that with an increase of σ_p , the ratio of Fo/Fv was decreased. For example, when σ_f was decreased 20% from the base condition, the ratio of Fo/Fv was increased from 0.8 to 1.0. This meant that the quality retention would benefit from reducing the σ_f within the range investigated.

The effects of the particle conductivity (σ_p) on process temperatures and lethality values are shown in Figure 17.4a and b. On the other hand, as the increase of σ_p caused reduction of the conductivity difference between carrier fluid and particles, particles with higher conductivity got higher temperatures at the entrance and the exit of the holding tube, and the carrier fluid thus showed higher temperatures at the end of the holding tube. Consequently, the accumulated lethality values at the end of holding tube for both carrier fluid and particles increased with σ_p . Fo/Fv was increased with σ_p as well, indicating that increasing the particle conductivity can improve the product quality.

Another finding from Figures 17.3 and 17.4 was that, when particle conductivity increased 20% from the base condition or carrier fluid conductivity decreased 20%, the particle temperature at the end of the holding tube would be higher than that of carrier fluid. From Table 17.1, it can be noted that the carrier fluid conductivity in the above case was still higher than that of particles. This meant

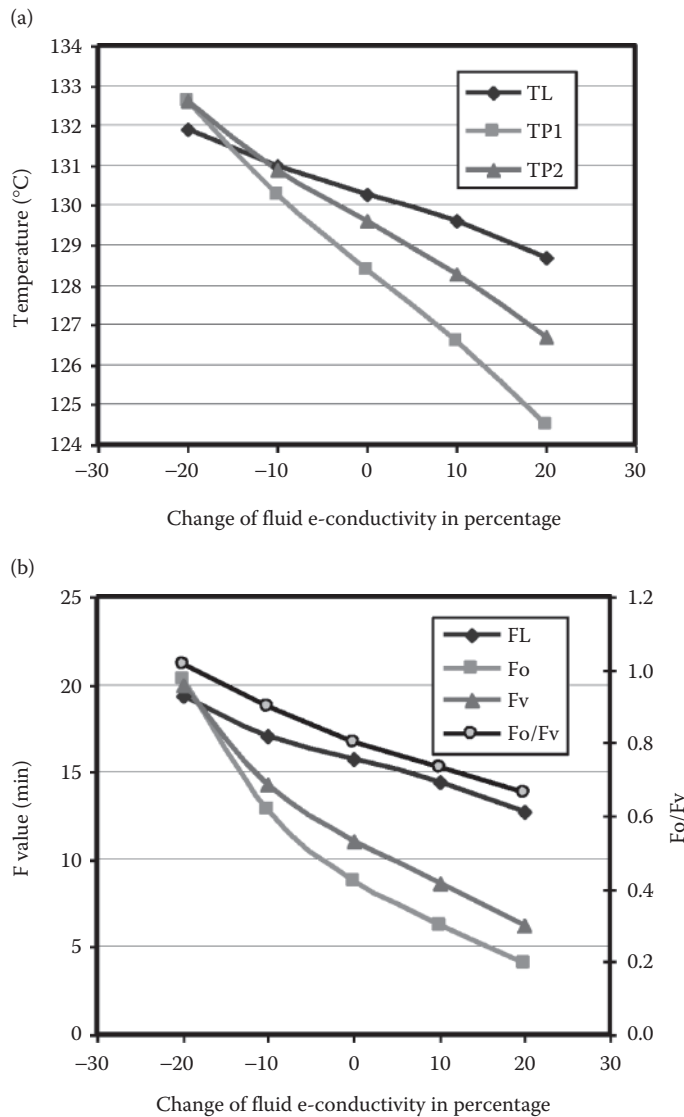


FIGURE 17.3 Effects of liquid conductivity (σ_f) on process temperatures and lethality values of both liquid and particles. (a) Effects of fluid e-conductivity on temperatures. (b) Effects of fluid e-conductivity on F values.

that particles could be heated faster than carrier fluid even though the conductivity of particles was lower than that of carrier fluid. This was consistent with Kim et al. (1996); they reported that fluid temperature increased about 9°C from an average of 130.5°C at the inlet of the holding tube to 139.5°C at the outlet of the holding tube.

17.6.2 THERMAL PROPERTIES

The effects of thermal properties including thermal diffusivity (D_p) of particles and surface heating transfer coefficient (h_{fp}) between carrier fluid and particles are shown in Figures 17.5 and 17.6. For the Ohmic heating process, the heat is generated inside foods by electricity; thus, the heating rate will be only dependent on the electrical field strength and electrical conductivity if the conductivity of foods being processed is uniform. However, in reality, for producing soup products containing

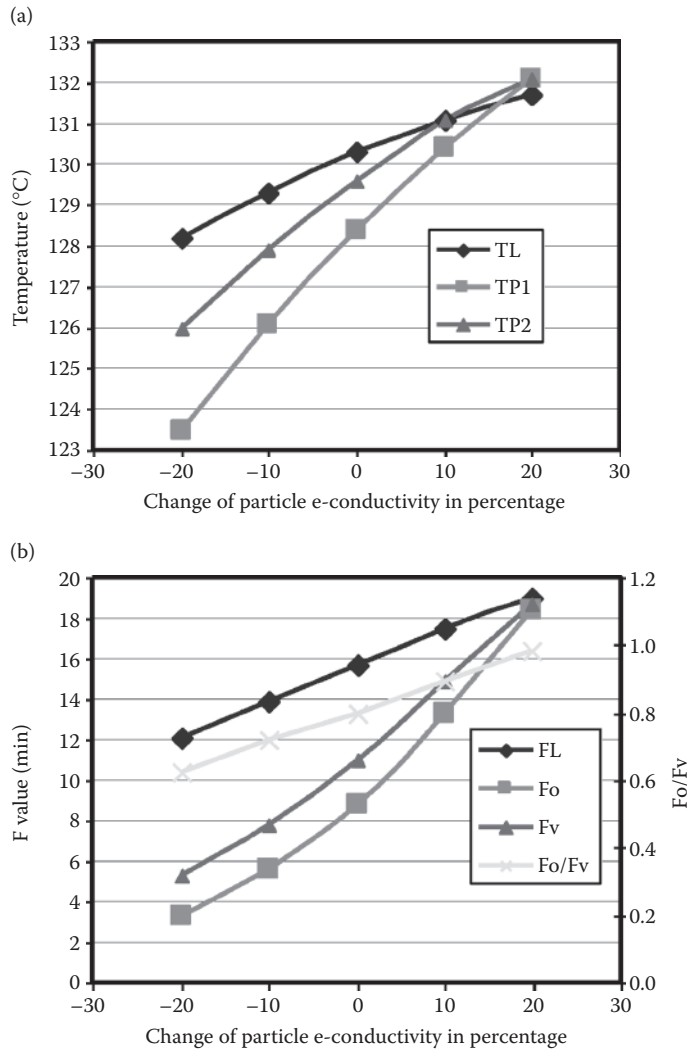


FIGURE 17.4 Effects of particle conductivity (σ_p) on process temperatures and lethality values of both liquid and particles. (a) Effects of particle e-conductivity on temperatures. (b) Effects of particle electrical conductivity on F values.

a variety of vegetable and meat particles, the carrier fluid usually have higher e-conductivity than particles because of some ingredients added in such as salt, resulting in the temperature difference between carrier fluid and particles during heating and holding processes. Therefore, the heat transfer between carrier fluid and particles during the heating and holding processes should be considered in determining their heating behaviors. From Figure 17.5a and 17.6a, it can be seen that with an increase of D_p and h_{fp} , the particle temperatures including the end of heating and of holding were increased, while the carrier fluid temperature at the end of the holding was also increased, but not as apparent as that of the particles. It is easily understood that the particles with higher D_p and h_{fp} obtained higher temperatures during the heating and holding time because they absorbed more heat from the carrier fluid. The higher carrier fluid temperature at the end of holding tube can be attributed to the higher particle temperature at the end of heating tube or the inlet of the holding tube, since the amount of heat transfer from carrier fluid to particles is dependent not only on h_{fp} and D_p but also on the temperature difference between carrier fluid and particle.

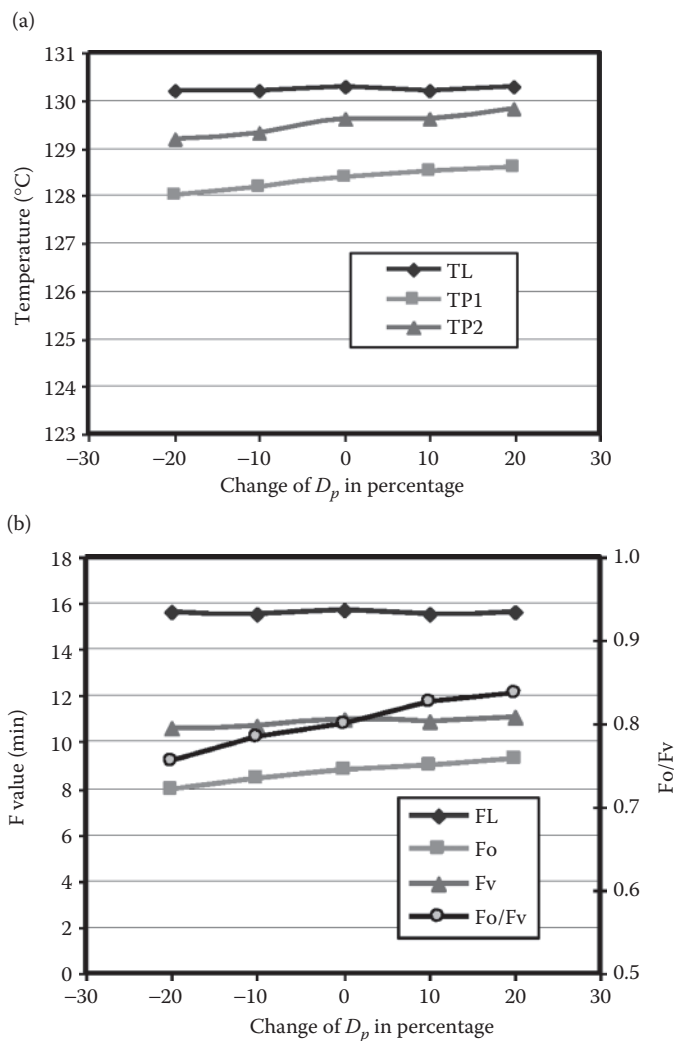


FIGURE 17.5 Effects of particle thermal diffusivity (D_p) on process temperatures and lethality values of both liquid and particles. (a) Effects of D_p on temperatures. (b) Effects of D_p on F values.

Based on Figures 17.5b and 17.6b, it was found that the Fo and Fv for particles increased with h_{fp} and D_p , but the ratio of Fo/Fv was affected mostly by D_p instead of h_{fp} . For example, when D_p increased 20% from base condition, the ratio of Fo/Fv was changed from 0.8 to 0.84, while the same percentage increase of h_{fp} only changed from 0.8 to 0.81. This indicated the D_p plays more important role than h_{fp} in the aspect of improving the quality retention for the soup products.

17.6.3 PARTICLE SIZE AND CONCENTRATION

The effects of particle size (S_p) and particle concentration (P_c) are shown in Figures 17.7 and 17.8. With the increase of particle size, the particle temperatures, including at the inlet and outlet of holding tubes, significantly dropped down while the carrier fluid temperature slightly decreased. This is due to the fact that the heating rate of particles is not only dependent on their electrical conductivity but also related to the heat transfer from carrier fluid to particle, if the carrier fluid is heated faster during the Ohmic heating process. Since the larger particle size induced more heat-transfer

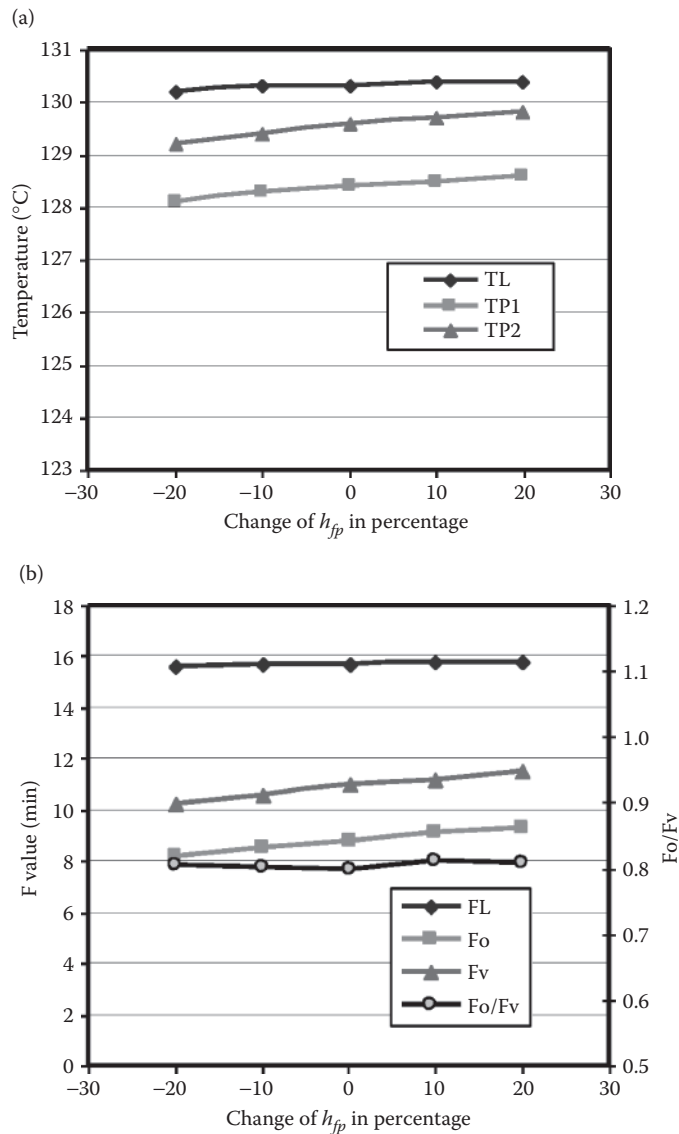


FIGURE 17.6 Effects of surface heat-transfer coefficient (h_{fp}) on process temperatures and lethality values of both liquid and particles. (a) Effects of h_{fp} on temperatures. (b) Effects of h_{fp} on F values.

resistance from the carrier fluid to particle center, the particles obtained less heat from the carrier fluid with a higher temperature. In addition, as the electrical conductivity is decreased with temperature, the particles with a lower temperature were heated slower due to the lower e-conductivity. Similarly, the accumulated lethality values including the particle center and the whole particle decreased with the particle size. For example, when the particle size from the base condition of 20 mm was increased to 24 mm (20%), the accumulated Fo and Fv values decreased from 8.8 to 7.2 min and from 11 to 9.8 min, respectively. The effect of the particle concentration was positive on the particle temperature, but negative on the carrier fluid temperature, as shown in Figure 17.8 with the ranges of particle concentration investigated. The reason causing a higher particle temperature

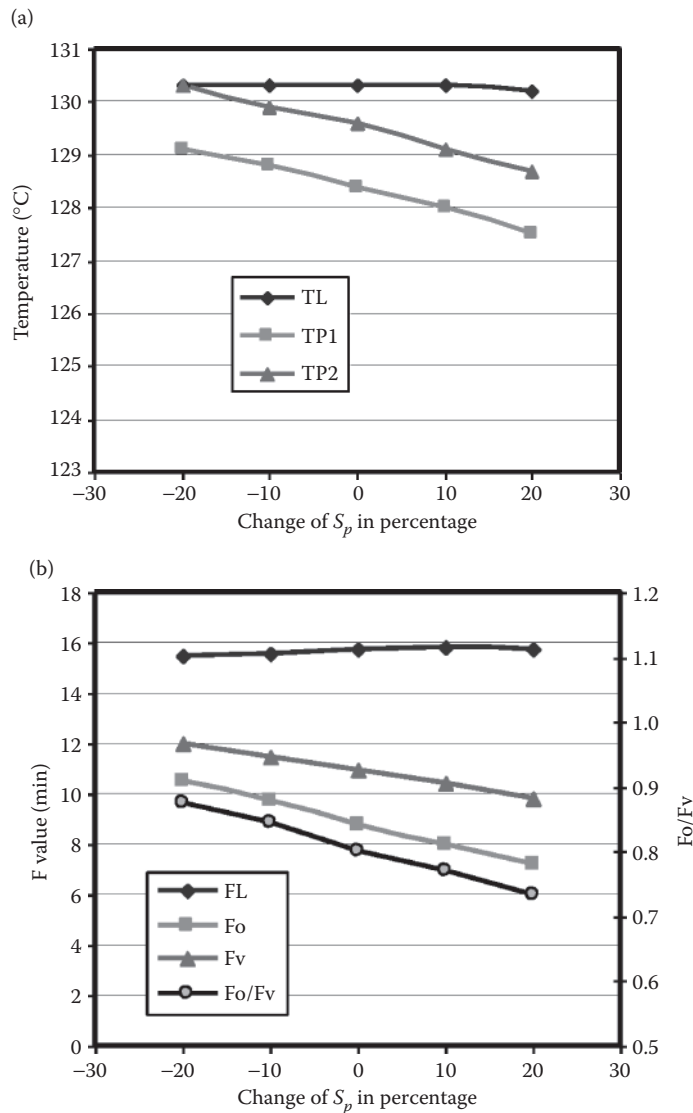


FIGURE 17.7 Effects of particle size (S_p) on process temperatures and lethality values of both liquid and particles. (a) Effects of S_p on temperatures. (b) Effects of S_p on F values.

with higher particle concentration can be explained from the electric circuit mode used for the computer model. As shown in Figure 17.1c, each element used for the calculation can be divided into two parts: E1 and E2. The resistance of E1 is determined by particles and the part of carrier fluid, while that of E2 is only dependent on the carrier fluid. With the increase of the particle concentration with a lower conductivity, the total resistance of E1 is increased. Since E1 and E2 are connected in a series, the higher resistant E1 part will generate more heat than the E2 part. Therefore, under a given carrier fluid temperature, the particle temperature will increase with the particle concentration that has a lower conductivity. On the other hand, the carrier fluid temperature dropping in the outlet of holding tube was due to the fact that the particle temperature was still lower than carrier fluid, absorbing more heat from the carrier fluid.

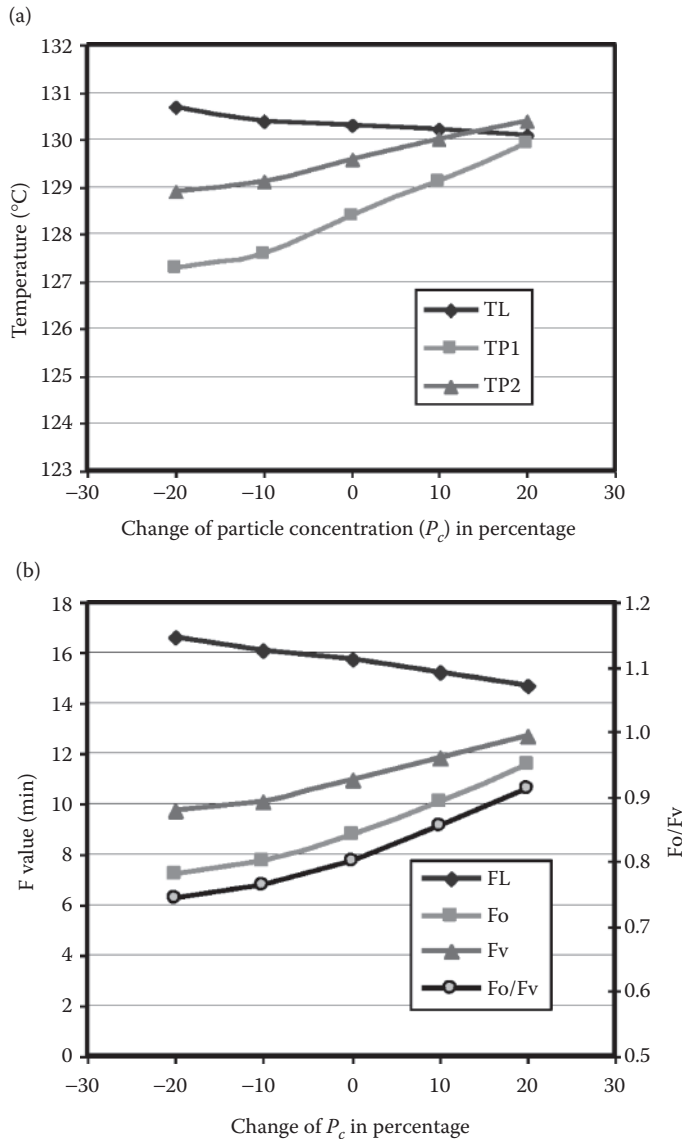


FIGURE 17.8 Effects of particle concentration (P_c) on process temperatures and lethality values of both liquid and particles. (a) Effects of P_c on temperatures. (b) Effects of P_c on F values.

17.6.4 INITIAL TEMPERATURE AND FLOW RATE

Figures 17.9 and 17.10 demonstrate the effects from the initial temperature (T_i) and flow rate (V_f) deviations on the process temperature and the accumulated lethality value. It can be seen that under a given process temperature (the carrier fluid temperature at the entrance of holding tube), increasing the initial product temperature resulted in higher temperatures of particles at both inlet and outlet including the carrier fluid at the outlet of the holding tubes, while increasing the flow rate induced a reverse result. Relatively, within the ranges investigated, the effects of the flow rate on the process temperature and Fo were more apparent than those of the initial temperature. For example, the particle temperature (TP1) at the entrance of the holding tube decreased from 128.5°C to

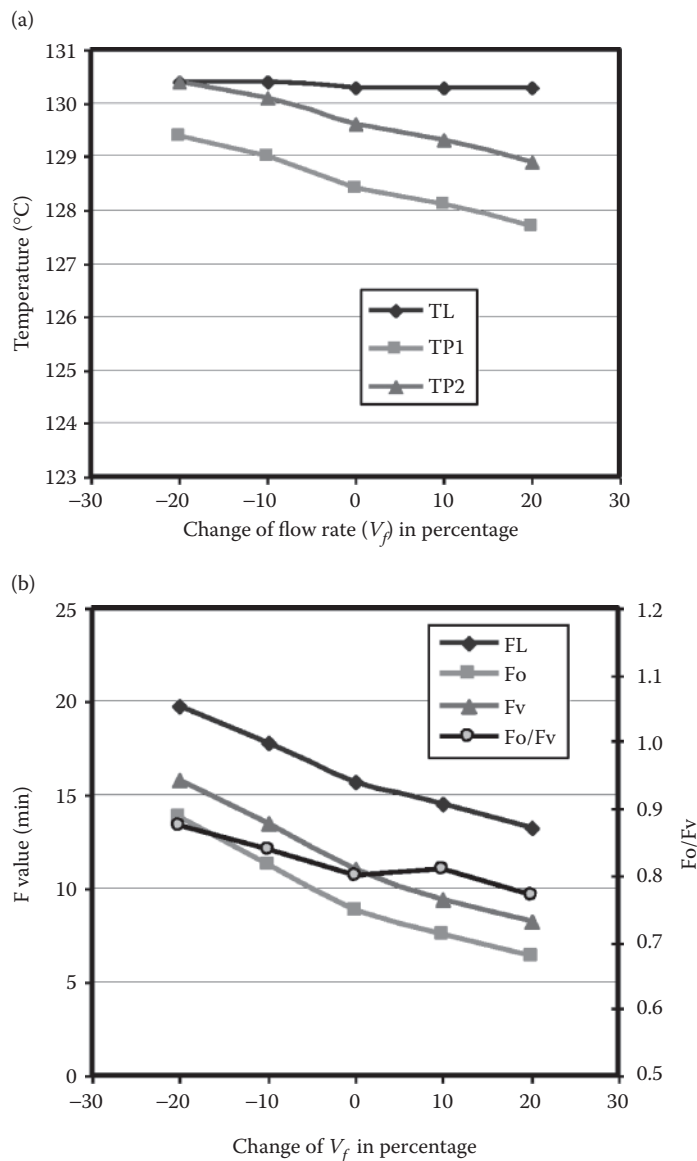


FIGURE 17.9 Effects of flow rate (V_f) on process temperatures and lethality values of both liquid and particles. (a) Effects of V_f on temperatures. (b) Effects of V_f on F values.

124.5 $^{\circ}\text{C}$ when V_f increased 20% from the base conditions, while it increased only from 128.5 $^{\circ}\text{C}$ to 129 $^{\circ}\text{C}$ when T_i increased the same amount as V_f . Correspondingly, a similar trend can be found for the lethality value from Figure 17.9b.

17.6.5 IMPORTANT ORDER OF INFLUENCING FACTORS

To determine the important order of main processing variables, the extreme differences of response variables between the lowest and highest values within the deviation ranges investigated are demonstrated in Table 17.3. From the table, it can be found that electrical conductivities of both carrier fluid and particles were the most important factors to all the response variables including process

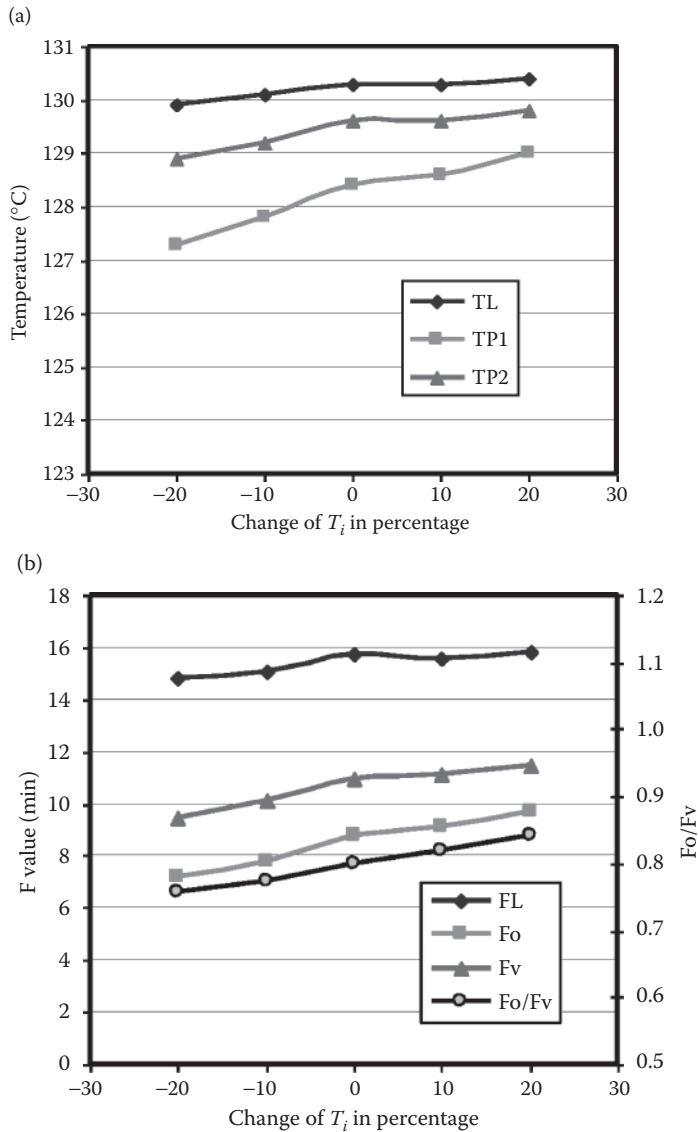


FIGURE 17.10 Effects of initial temperature (T_i) on process temperatures and lethality values of both liquid and particles. (a) Effects of T_i on temperatures. (b) Effects of T_i on F values.

temperatures and accumulated lethality values for both carrier fluid and particles, but their affecting trends were opposite. Within the deviation ranges investigated, the effect of σ_f was negative, while that of σ_p was positive. The flow rate (V_f) can be considered as a second important factor, but it only affected the accumulated lethality values for both carrier fluid and particles. This is because of the assumption that the process temperature at the end of the holding tube was always kept at a constant temperature of 133°C. The effects from particle size (S_p), particle concentration (P_c), and initial temperature (T_i) are three important factors special to the process temperatures and lethality values of particles. Within the deviation ranges investigated, the effects from thermal properties including D_p and h_{fp} were very small compared to other factors. The details for important orders of all investigated process variables were determined as follows:

TABLE 17.3

Extreme Differences of Response Variables between Minimum and Maximum Values within the Deviation Ranges Investigated

	TL	TP1	TP2	FL	Fo	Fv	Fo/Fv
σ_f	-3.2	-8.1	-5.9	-6.6	-16.2	-13.8	-0.35
σ_p	3.5	8.6	6.1	6.9	15.1	13.4	0.36
D_p	0.1	0.6	0.6	0	1.3	0.5	0.08
h_{fp}	0.2	0.5	0.6	0.2	1.1	1.3	0.005
S_p	-0.1	-1.6	-1.6	0.2	-3.3	-2.2	-0.14
P_c	-0.6	2.6	1.5	-1.9	4.4	3	0.17
V_f	-0.1	-1.7	-1.5	-6.6	-7.4	-7.5	-0.10
T_i	0.5	1.7	0.9	1	2.5	2	0.08

For TL: $\sigma_p > \sigma_f > P_c > T_i > h_{fp} > D_p = S_p = V_f$

For TP1: $\sigma_p > \sigma_f > P_c > V_f = T_i > S_p > D_p > h_{fp}$

For TP2: $\sigma_p > \sigma_f > S_p > P_c = V_f > T_i > h_{fp} = D_p$

For FL: $\sigma_p > \sigma_f = V_f > P_c > T_i > h_{fp} = S_p > D_p$

For Fo: $\sigma_f > \sigma_p > V_f > P_c > S_p > T_i > D_p > h_{fp}$

For Fv: $\sigma_f > \sigma_p > V_f > P_c > S_p > T_i > D_p > h_{fp}$

For Fo/Fv: $\sigma_p > \sigma_f > P_c > S_p > V_f > T_i = D_p > h_{fp}$

17.7 CONCLUDING REMARKS

Process sensitivity analysis is essential for process development and evaluation. It is especially useful for Ohmic heating method-based thermal processes, which are relatively new and cover more sensitive variables. The information presented in this chapter can be useful for understanding how major processing variables of continuous Ohmic heating processing systems affect the required process target variables and can be further used as a protocol for both process establishment and optimization purposes.

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Section 7

*Ohmic Heating as Applied to
Specific Foods*

18 Ohmic Heating of Muscle Foods (Meat, Poultry, and Fish Products)

James G. Lyng

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18.1 INTRODUCTION

Ohmic heating is a term used to describe direct electrical resistance heating of food products. It is a technology many review and popular articles have been written about including recent examples by Sastry (2005), Vicente et al. (2006), and Vicente and Castro (2007). The current chapter aims to overview the use of Ohmic heating for processing muscle foods. As the majority of the more recent work published on these products has concentrated on the use of this technology for heat processing (and in particular pasteurizing) meats such as beef, poultry, and pork, this will be the main focus

of this chapter. However, some work has also been performed on fish, in particular in the area of surimi processing, and this work will also be reviewed.

18.2 THE PRINCIPLES OF OHMIC HEATING

18.2.1 FUNDAMENTAL CIRCUITRY

An electrical circuit is characterized by three physical quantities, namely voltage, amperage, and resistance. Voltage (volts) is the electrical pressure supplied by a main AC supply, battery, alternator, or generator. Resistance (ohms) is the opposition to the current flow caused by the circuit (e.g., wires, electrical components, or food [in the case of Ohmic heating]) while amperage (amperes) is the current flow through the wires, electrical components, or food. As these physical quantities are quite abstract so, the analogy of a garden hose connected to a tap is often used to assist in their visualization. When the tap is opened fully, there is good water pressure (electrical pressure [voltage]) and a substantial water flow (current flow [amperage]) through the hose (wires, electrical components, or food). Squeezing the hose (increasing resistance) will decrease the water flow (decrease electrical current) but will not change water pressure (electrical pressure [voltage]). If on the other hand the water is allowed to flow through the hose normally but the tap is closed to the half-way position, the water pressure (electrical pressure [voltage]) in the hose will decrease as will the water flow (current flow [amperage]), though no change in the resistance will occur. The mathematical relationship between these three fundamental electrical quantities (applied to circuits containing only resistive elements [i.e., no coils]) is one of the most important, basic laws of electricity and is known as Ohm's law (Equation 18.1).

$$V = I \times R \quad (18.1)$$

where V is the voltage (volts), I is the amperage (amperes), and R is the resistance (ohms, Ω).

18.2.2 OHMIC HEATING MECHANISMS

To Ohmically heat a material it must be capable of conducting an electrical current. For a material to be classified as a conductor, electrical charges must be able to move from one point to another within it to complete an electrical circuit (Brady and Humiston, 1986). Muscle foods, while generally containing relatively high levels of water (Chan et al., 1995, 1996), are regarded as solid materials. When it comes to conducting electricity, solids such as metals generally display metallic conduction due to the relatively free movement of electrons through metallic lattices. Muscle foods, on the other hand, behave like electrolytic solutions, conducting electricity through electrolytic conduction. A description of ion flow in an electrolytic cell connected to a DC source can be found in any basic electrochemistry textbook. When an electrolytic solution is placed in contact with a pair of electrodes to which a DC source is connected, mobile positive ions present in the product (e.g., Na^+) migrate toward the negative electrode (cathode), and mobile negative ions (e.g., Cl^-) move toward the positive electrode (anode). At the negative electrode (which has an excess of electrons), the positive ions pick up electrons and are reduced while at the positive electrode (which has a deficiency of electrons) the negative ions give up electrons and are oxidized. If the current supply used in Ohmic heating was DC, electrode polarization would rapidly occur. Therefore, to prevent this AC current is used as the cyclic change (generally low frequency 50 Hz in Europe or 60 Hz in USA) in current direction allowing insufficient time for appreciable polarization to occur as the electrochemical reactions described above are considered undesirable in Ohmic heating. As a further preventative measure against their occurrence electrodes are often constructed from titanium or titanium coated with colloidal deposits of "platinum black" to facilitate the adsorption of the extremely small quantities of electrode reaction products. In addition, work by Samaranayake et al.

(2005) has shown that further reductions in electrochemical reactions in stainless steel, titanium, and platinized-titanium electrodes can be achieved by changing the pulse characteristics from traditional 60 Hz, sine wave pulses to bipolar pulses of 10 or 4 kHz. The effect of differing pulse width and delay times are also discussed in this chapter.

When a muscle food conducts electricity by electrolytic conduction, the moving ions within it collide with other molecules and these collisions lead to momentum transfer to these molecules, which in turn increases their kinetic energy thereby heating the product. de Alwis et al. (1989) state that the interaction between the local field strength and local electrical conductivity will govern the local heat generation rate (Equation 18.2)

$$Q = E^2\sigma = \lambda J^2 \quad (18.2)$$

where Q is the heat generation rate per unit volume (W m^{-3}), E is the electrical field strength (V cm^{-1}), σ is the electrical conductivity (S m^{-1}), λ is the resistivity ($\Omega \text{ m}$) and J is the current density (A m^{-2}). The actual heating rate for the substance can then be calculated from Equation 18.3 (de Alwis and Fryer, 1990)

$$\frac{dT}{dt} = \frac{Q}{\rho C} \quad (18.3)$$

where, ρ is the density (kg m^{-3}) and C is the specific heat capacity ($\text{kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$). ρC is often referred to as the volumetric heat capacity (i.e., the amount of heat energy that is required to raise the temperature of one cubic meter of the substance by 1°C). Equation 18.3 shows that a high Q does not guarantee a rapid rate of temperature rise, which is also dependent on ρC .

18.2.3 FACTORS INFLUENCING THE OHMIC HEAT RATE IN MUSCLE FOODS

18.2.3.1 Electrical Field Strength

The electrical field strength (E) can be varied by adjusting the gap between the electrodes or by changing the applied voltage.

18.2.3.2 Electrical Conductivity

de Alwis et al. (1989) stated that the electrical conductivity (σ) of a product determines its suitability for Ohmic heating. Piette et al. (2001) claimed that it is theoretically possible to provide any food with enough Ohmic power to generate a target temperature rise. However, this will require using increasingly large current densities or increasingly large electrical field strengths when σ values become very large or very small, respectively (Equation 18.2). However, these workers also state that in reality various considerations related to safety, cost, and product quality limit the electrical field strength and current density that can be used in practice. Overall, these workers suggest that Ohmic heating is only possible between a certain range of σ values ($0.01\text{--}10 \text{ S m}^{-1}$) and that it works optimally in the range of $0.1\text{--}5 \text{ S m}^{-1}$.

18.2.3.2.1 Temperature Effects on Electrical Conductivity

The σ of food products generally increases with temperature and it is believed that this increase is mainly due to increased ionic mobility (Parrott, 1992), which is most likely due to structural changes in tissues (e.g., cell wall breakdown, softening, and reduced phase viscosity). Shirsat et al. (2004b) showed that the conductivity of model and commercial meat batters increased with temperature across a range of $15\text{--}80^\circ\text{C}$ (Figure 18.1a). Sarang et al. (2008) measured the σ in a range of chicken, pork, and beef meats (with fibers oriented perpendicular to the electric field) across a

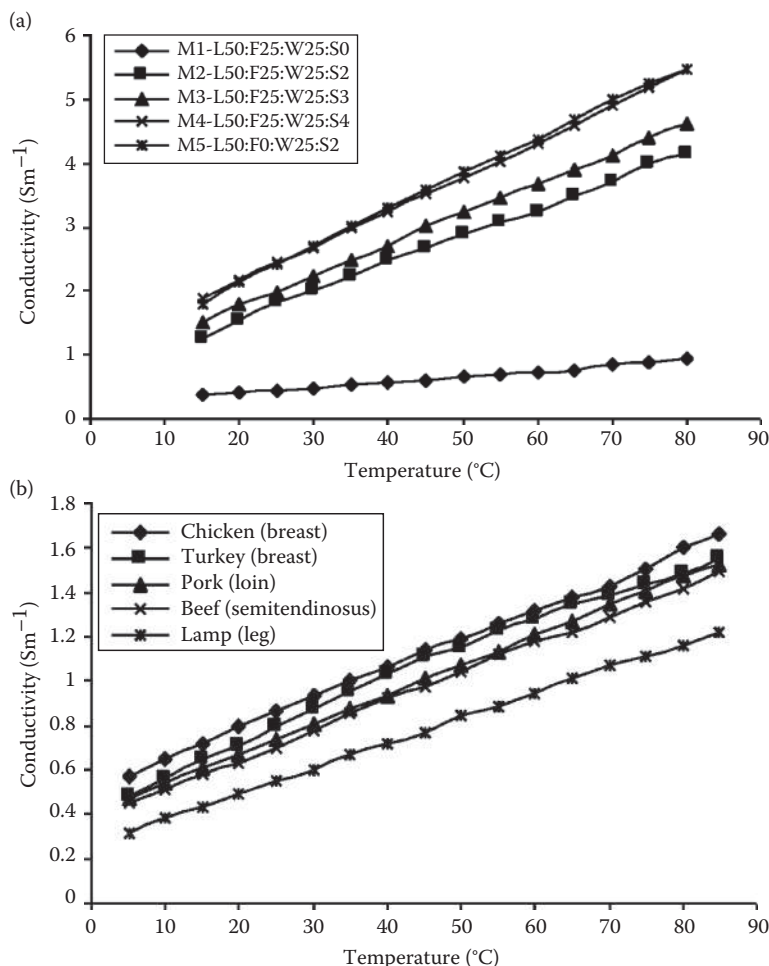


FIGURE 18.1 (a) The effect of temperature on the electrical conductivity of model meat formulations (M1–M5) containing different proportions of lean muscle (L), fat (F), water (W), and salt (S). (From Shirsat, N. et al. 2004b. *Journal of Muscle Foods* 15: 121–137.) (b) Electrical conductivities of unsalted lean meats from five meat species. (Reprinted from *Meat Science*, 83, Zell, M. et al. Ohmic heating of meats: Electrical conductivities of whole meats and processed meat ingredients, 563–570, Copyright (2009b), with permission from Elsevier.)

temperature range 25–140 $^{\circ}\text{C}$ and reported a linear increase in conductivity with temperature during Ohmic heating at a constant voltage gradient. Zell et al. (2009b) also found a linear increase in the σ in a range of lean meats (chicken, turkey, pork, beef, and lamb) across a temperature range of 5–85 $^{\circ}\text{C}$ (Figure 18.1b). Both research teams noted that chicken breast had the highest σ of the meat species examined. A similar effect of temperature on σ was also illustrated by Piette et al. (2004). This phenomenon is often factored into the design of continuous Ohmic heaters for pumpable fluids. In these heaters, which have multiple heating sections, the spacing between electrodes is often increased toward the outlet to ensure that each heating section has the same electrical impedance. In something of a contrast, the findings of Bozkurt and Icier (2010) do not fully agree with the above. These workers found an increase in σ of minced beef fat blends (containing 2%, 9%, 15%, and 90% fat) with increasing temperature but only up to a “critical” initial cooking temperature (60–70 $^{\circ}\text{C}$ depending upon fat content) above which either a plateau or decline in conductivity was noted.

18.2.3.2.2 *The Effects of Product Formulation on Electrical Conductivity*

Of the work that has been published in this area on muscle foods, the vast majority is in the area of meat and meat products. These products are generally formulated to contain meat and nonmeat ingredients. It is through this blend that the electrical current flows during Ohmic heating.

18.2.3.2.2.1 *Muscle Food Constituents* Compared to fat, lean has a much higher electrical conductivity, with Sarang et al. (2008) reporting conductivities of lean chicken, pork, and beef samples in the ranges 0.444–0.665, 0.532–0.584, and 0.371–0.491 S m⁻¹ at 25°C. Shirsat et al. (2004a) showed noncomminuted lean pork samples fell in the conductivity range of 0.64–0.76 S m⁻¹ at 20°C. Noncomminuted lean meat is a complex structure consisting of muscle fibers; connective tissue with a certain amount of intramuscular fat (marbling) also occurring within the tissue. The diversity and complexity of components in the muscle fiber coupled with the involvement of some of these entities in muscle contraction and the integration of connective tissue throughout the muscle make it difficult to precisely visualize the passage of electrical current through lean meat during Ohmic heating. The following section briefly overviews these components.

Muscle Fibers: Muscle cells or fibers are generally 10–100 µm in diameter (Honikel, 1992) but can vary in length from a few millimeters to tens of centimeters or more (Skaara and Regenstien, 1990; Gault, 1992). The components of the muscle cell are described in more detail by Lyng and McKenna (2007), but essentially consist of the sarcolemma (a thin double-layered outer membrane), sarcoplasm (cytoplasm of the muscle fiber), sarcoplasmic reticulum, and T-tubules (a system which controls muscle contraction and relaxation), sarcolemmal cytoskeletal proteins (intracellular structures that hold the contractile apparatus in register, maintain cell structure, interconnect organelles to each other and often attach to the cell membrane) and the myofibrillar proteins or contractile apparatus (up to 1000 of these 1–2 µm diameter myofibrils occupy approximately 80% of the muscle cell volume and run the entire length of the cell).

Connective Tissue: Muscle connective tissue comprises fibrous proteins collagen, elastin, and reticulin (Pearson and Young, 1989), ground substances and cells (Asghar and Pearson, 1980). Muscular connective tissue may be sub-divided into the endo- peri-, and epi-mysium depending on its location within the muscle. The endomysium is a layer that surrounds individual muscle cells, which in turn are grouped into bundles surrounded by connective tissue known as the perimysium. These bundles of cells together form the muscle that is itself surrounded by an outer layer known as the epimysium (Light et al., 1984).

Fat: Relative to lean, Shirsat et al. (2004a,b) showed the σ of pork fat is very low (0.01–0.09 S m⁻¹ at 20°C) while Sarang et al. (2008) found conductivities for chicken fat to be of a similar order of magnitude (0.035 S m⁻¹ at 25°C). In the preparation of some meat products, fat trimmings are added to lean to form a blend. Shirsat et al. (2004a) presented a graph (Figure 18.2a) showing the effect of added fat (0–100%) on the conductivity of a lean-fat blend. This graph shows the poorly conductive nature of fat vs. the conductivity of lean, minced muscle. However, these workers suggested the relationship between fat content and conductivity appears to be asymptotic rather than linear. As the percentage of fat in lean was reduced, the conductivity of lean increased until the level of fat (<10%) had a limited effect on the conductivity of the mixture. Shirsat et al. (2004a) suggested that the addition of fat to lean could possibly influence the conductivity of the mixture in two ways: (a) reduction due to the poor conductivity of the fat (b) coating of lean particles with fat thereby creating a barrier for the passage of electrical current.

While fat is added in the preparation of some meat products, there is also a certain amount of endogenous fat present in most meats. Sarang et al. (2008) did not find a strong relationship ($R^2 < 0.0503$) between endogenous fat content (1.32–7.39%) and electrical conductivities of lean meat cuts. Zell et al. (2009b) compared the effect of added fat (2.35–15.16% measured fat content) vs. endogenous fat (0.45–3.75% measured fat content) on σ of meats at 65°C (chosen as all fat would be melted at this temperature). In contrast to the observations of Sarang et al. (2008), Zell et al. (2009b)

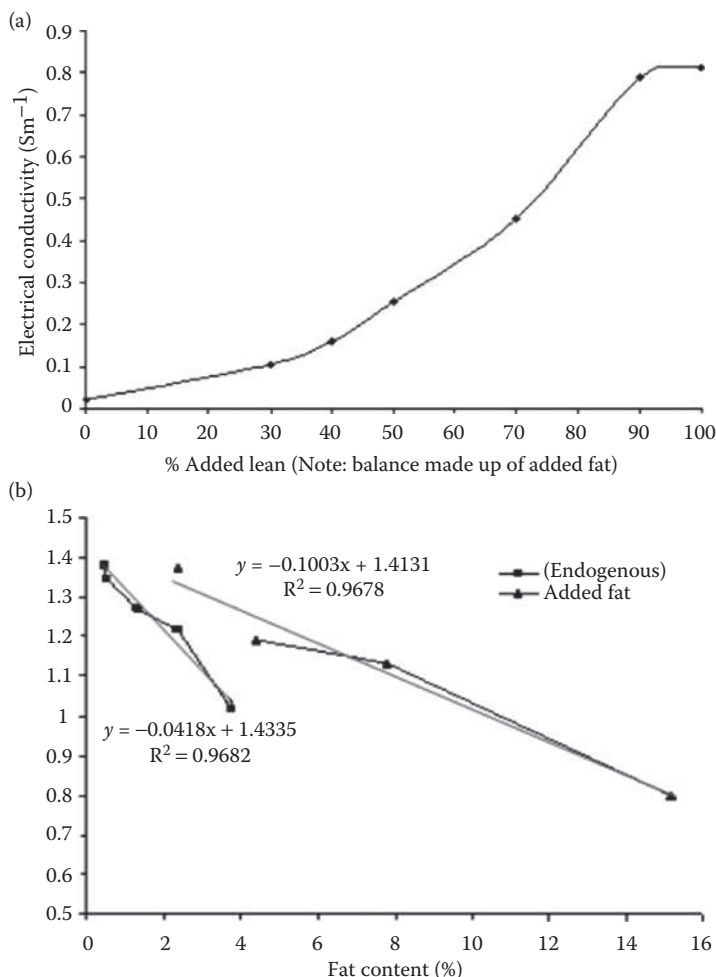


FIGURE 18.2 (a) The effect of added fat (0–100%) on the conductivity of a lean-fat blend. (From Shirsat, N. et al. 2004a. *Meat Science* 67: 507–514.) (b) Effect of endogenous vs. added fat on electrical conductivity of meats measured at 65°C. (Reprinted from *Meat Science*, 83, Zell, M. et al. Ohmic heating of meats: electrical conductivities of whole meats and processed meat ingredients, 563–570, Copyright (2009b), with permission from Elsevier.)

found a linear decrease in σ as added (2.35–15.16%) or endogenous (0.45–3.75%) fat increased. In addition these workers also noted a more pronounced effect from increasing endogenous fat, suggesting it has a greater impact on conductivity than incorporated fat (Figure 18.2b).

18.2.3.2.2.2 Muscle Food Product Manufacture: Influence of Non-Meat Ingredients Although lean and fat meats are principle ingredients in processed meat products, other nonmeat ingredients are usually incorporated which have various functions. Examples of such ingredients include salt (flavor, water binding, and preservation), seasoning (flavor), nitrates and nitrites (color and antimicrobial), proteins (increase nutritional value and gelation aid), and bulking agents such as starch and artificial colorings. If the addition of these ingredients to the product increases the amount of mobile ions in the product (i.e., the ingredients are electrolytic) the σ will increase, which in turn will increase the rate of Ohmic heating. A relative ranking of nonmeat ingredients in terms of their electrical conductivities is presented by Zell et al. (2009b). In this study, 5% aqueous solutions/suspensions of

nonmeat ingredients were prepared and their electrical conductivities were subsequently measured at 25°C and 80°C. At the higher temperatures the conductivity values were approximately 2.5 times higher. These workers found nonmeat ingredients such as deionized water and nonionic carbohydrates (e.g., sucrose, starch, glucose, and fructose), had extremely low σ values ($<0.03 \text{ S m}^{-1}$) while ionic carbohydrates (e.g., carageenan) and proteins (e.g., soya protein isolate, sodium caseinate) had somewhat higher ($0.1\text{--}0.5 \text{ S m}^{-1}$) conductivities. Monosodium glutamate, sodium ascorbate, sodium benzoate, and Red 2G all displayed intermediate conductivities ($1\text{--}2.5 \text{ S m}^{-1}$) while solutions containing sodium nitrate, sodium nitrite, and sodium chloride had σ values above 2.5 S m^{-1} . The σ results for these solutions gave strong correlations with dielectric loss factors (ϵ'') at selected radio and microwave frequencies (27.12 and 1850 MHz, respectively) for similar ingredients presented by Lyng et al. (2005).

18.2.3.2.2.3 Blended Meat Products To further study the effects of salt and fat on conductivity and Ohmic heating times, a number of model meat emulsion formulations with different salt levels and also a formulation with no added fat, were prepared by Shirsat et al. (2004b) using shoulder lean and back fat. Results indicate that salt or other electrolytic ingredients were essential for Ohmic heating and for a given batter an increase in salt content increased σ and increased Ohmic heating rate ($P < 0.001$) (Figure 18.3). In relation to fat, Shirsat et al. (2004b) also noted an increase in fat content caused a reduction in conductivity ($P < 0.001$) leading to an increase in Ohmic heating time ($P < 0.001$). Piette et al. (2004) also reported that increasing salt content (1–2.5%) in pseudo ham resulted in a linear increase in σ while increasing fat content (10–30%) in bologna sausages lead to a linear decrease in σ . Zell et al. (2009b) presented results for the σ (5–85°C) of beef blends to which a range of ingredients were added at their typical usage levels (including pork back fat [5–20% w w⁻¹], water [25% w w⁻¹], gluten [0.15% w w⁻¹], potato starch [4% w w⁻¹], sodium nitrite [0.015% w w⁻¹], phosphate [3% w w⁻¹], and sodium chloride [1.5–2.5% w w⁻¹]). The effect of fat is discussed in Section 18.2.3.2.2.1. Water at 25% inclusion had an obvious dilution effect on ionic concentrations,

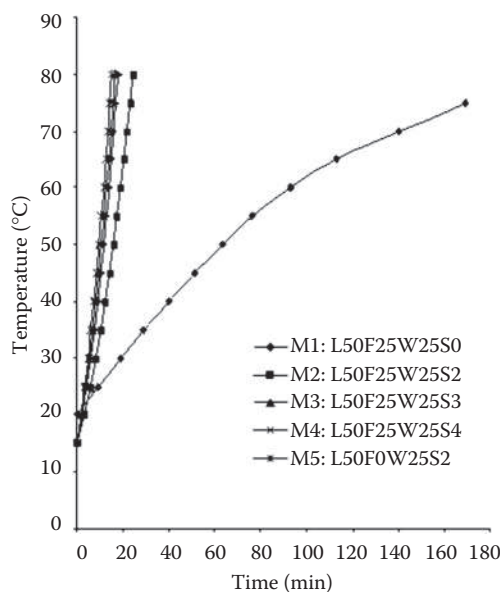


FIGURE 18.3 Time–temperature Ohmic heating profile (constant voltage density of 4 V cm^{-1}) of model meat formulations (M1–M5) containing different proportions of lean muscle (L), fat (F), water (W), and salt (S). (Shirsat, N. et al. Conductivities and Ohmic heating of meat emulsion batters. *Journal of Muscle Foods*. 2004b. 15: 121–137. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.)

leading to lower σ values. The other nonionic ingredients had very little effect on the σ of beef. As expected, the ionic ingredients had a profound effect on beef conductivity when added at their normal inclusion levels, with the exception of sodium nitrite (due to its very low addition level).

18.2.3.2.2.4 The Effect of Ingredient Distribution in Meat Products *Comminuted Meats:* Nonmeat ingredients are generally added to comminuted meat batters during a bowl chopping procedure. Uneven distribution of ionic nonmeat ingredients (e.g., salt, phosphate, nitrate, etc.) through a product could lead to uneven Ohmic heating and, therefore, care should be taken to ensure that bowl chopping procedures are of sufficient duration and intensity to thoroughly blend these ingredients throughout the batter.

Noncomminuted Meats: For wet-cured noncomminuted products such as ham, nonmeat ingredients are generally added to a product via brine normally injected into the product using a multineedle injector. This brine is further distributed throughout the product during a tumbling procedure. Similar to bowl chopping, care should be taken to ensure that injection and tumbling procedures are sufficient to ensure a uniform distribution of ionic nonmeat ingredients through the product. Zell et al. (2009c) evaluated the uniformity of the salt distribution in beef destined for Ohmic heating following a variety of agitated soakings, or injections and tumbling techniques. A final preparation method (multi-injection, five points) with a 3% salt solution followed by a 16 h tumbling was found to give the most uniform salt distribution.

18.2.3.2.2.5 The Effect of Comminution on Electrical Conductivity In the manufacture of meat and meat products, the extent of size reduction varies from highly comminuted meat emulsions (e.g., frankfurter and luncheon roll batters) to minced products to noncomminuted products (e.g., selected ham and beef products).

Highly Comminuted Meat: The majority of the in-depth studies on Ohmic heating of meat conducted to date have focused on highly comminuted meats and meat emulsions. The manufacture of such products involves breaking down the connective tissue, myofibrillar, and intramuscular fat networks of entire meats during extensive bowl chopping. As a result, the microstructure of meat emulsions is relatively homogenous and consists of fat droplets coated with soluble proteins (emulsifying agents) suspended in an aqueous medium containing soluble proteins, segments of myofibrils, connective tissue fibers, and other soluble muscle constituents (Figure 18.4a). In addition, these products are formulated to include a range of nonmeat ingredients (e.g., salt, starch, seasoning, etc.) some of which are ionic in nature. When an alternating current is applied to such a matrix in an Ohmic heater, it is most likely that dissociated ions will oscillate back and forth within the aqueous medium at 50–60 Hz, leading to heating of the product. Fat, which is a poor conductor, has been reduced in size and therefore the current can easily flow around the dispersed fat globules.

Noncomminuted Meat: In contrast, the structure of meat in its entirety is considerably more complex (Section 18.2.3.2.2.1) as the muscle fiber and connective tissue (epimysium, perimysium, and endomysium) structures are still intact and there will be a certain amount of intramuscular fat (marbling) within the tissue (Figure 18.4b). To further complicate matters in many muscles, fibers change direction along the length of the muscle. As a result, the potential pathways for the passage of electrical current will be considerably more complex and nonconductive fat deposits are potentially larger, providing greater obstacles to current flow. In emulsions, direction is not really a major issue due to homogeneity of the structure, but in entire meats, the relative positioning of electrodes parallel or perpendicular to myofibrillar and connective tissue structure could provide very different pathways for the movement of ions within the product. Zell et al. (2009b) found that σ values of salted and unsalted beef *Semitenndinosus* measured in a direction parallel to the fiber orientation were higher than those measured in a perpendicular fashion, and stated that this reflected a greater ease of current flow along the muscle fibers rather than in a cross-fiber direction. These workers suggested heating time reductions of approximately 8% (unsalted) and 15% (salted) for samples heated in parallel vs. perpendicular orientation to the current flow

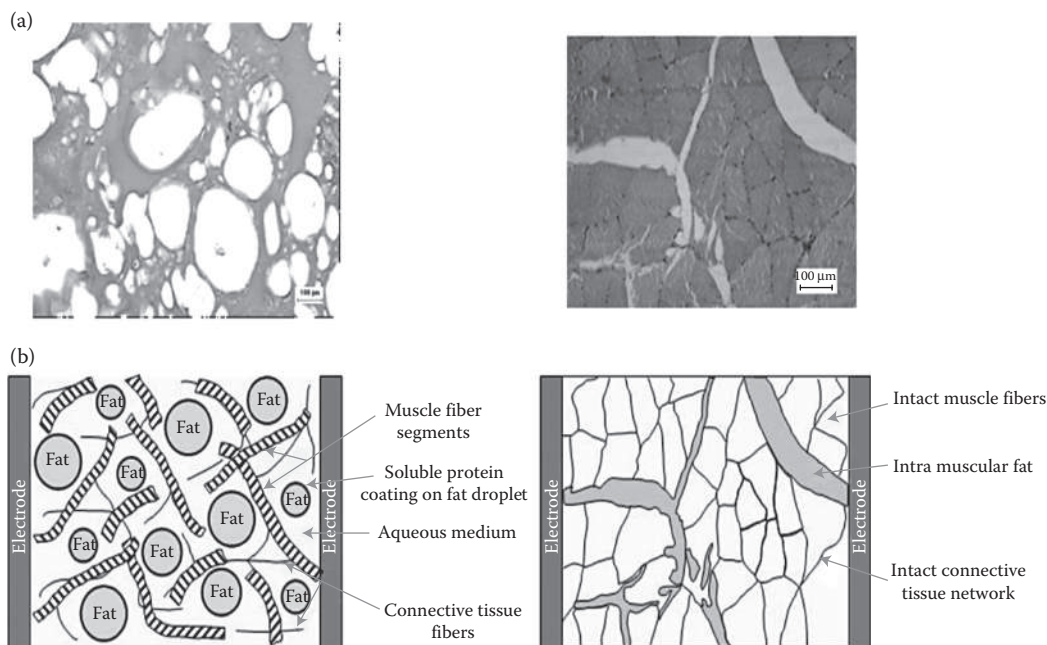


FIGURE 18.4 Images. (From Shirsat, N. et al. 2004a. *Meat Science* 67: 507–514; Shirsat, N. et al. 2004d. *Journal of the Science of Food and Agriculture* 84: 1861–1870.) Schematic diagrams showing the microstructure of (a) highly comminuted meat emulsion (b) entire meat in contact with a pair of electrodes. (Note schematics from Lyng, J.G. and McKenna, B.M. 2007. In: *Food Machinery Design Handbook: Farming, Processing and Packaging*, pp. 553–578. William Andrew Inc. New York.)

(Figure 18.5). The inferior σ in the perpendicular direction had also been commented on by Saif et al. (2004) and Sarang et al. (2008).

Minced Meat: Mincing, while less severe than bowl chopping, also disrupts the connective tissue and cellular structure of meat and Shirsat et al. (2004a) suggested different effects of the mincing on the conductivities of lean vs. fat. Minced lean had higher σ compared to its nonminced counterpart and a possible explanation given for this increase was the release of moisture and inorganic constituents from myofibrillar minced tissue. Zell et al. (2009b) also compared the electrical conductivities of unsalted noncomminuted (measured parallel or perpendicular to the fiber direction) and minced beef, and found the minced showed the highest σ (Figure 18.5). In contrast, Shirsat et al. (2004a) found the conductivities of minced fat were lower than the entire fat. While these workers took measures to minimize incorporated air in the sample material (which could reduce conductivity), they also suggested the disruption of the connective tissue network running through the fat (which could have provided a pathway for a small amount of current to flow) could have also contributed to the observed changes.

18.2.3.2.2.6 Anatomical Location vs. Electrical Conductivity In addition to the points raised in Section 18.2.3.2.2, Shirsat et al. (2004a) suggested the anatomical location of a muscle could also influence its σ . These workers found that the σ of a noncomminuted leg lean was significantly ($P < 0.01$) higher than shoulder lean (0.75 vs. 0.64 S m⁻¹). Following an examination of samples using light microscopy, Shirsat et al. (2004a) suggested this difference could be due to a denser muscle fiber structure, greater amounts of connective tissue and/or higher intra-muscular fat in shoulder vs. leg. Sarang et al. (2008) also found some significant differences in the σ of chicken samples from different anatomical locations with pork and beef cuts from different locations also showing some differences.

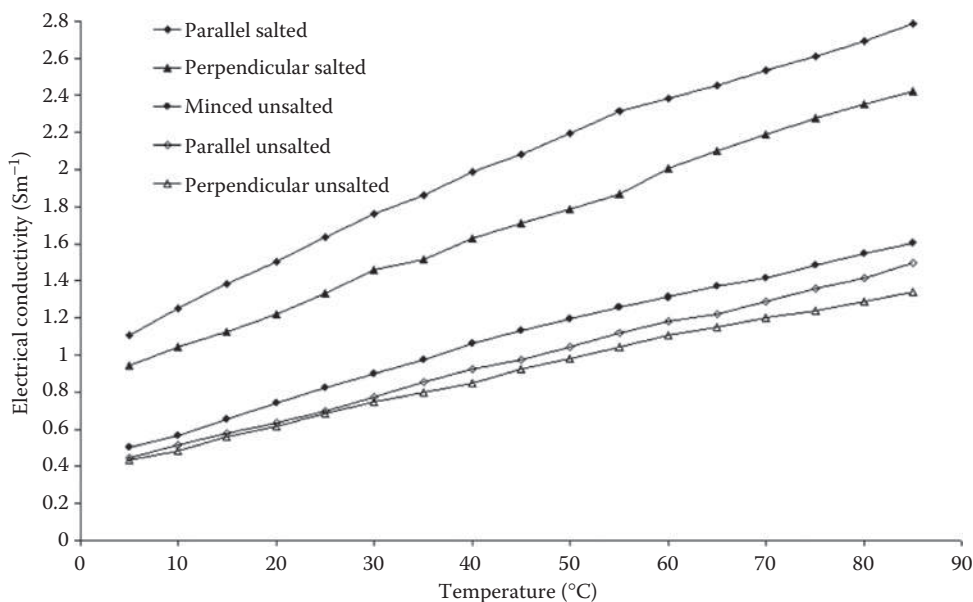


FIGURE 18.5 The effect of fiber direction, mincing and salting on the electrical conductivity values of beef (*Semitendinosus*). (Reprinted from *Meat Science*, 83, Zell, M. et al. Ohmic heating of meats: electrical conductivities of whole meats and processed meat ingredients, 563–570, Copyright (2009b), with permission from Elsevier.)

18.3 HEAT PROCESSING OF MEATS

Preservation of meat by thermal processing dates back to the beginning of the 19th century when in 1810 Nicolas Appert, while not aware of the nature of the process involved, found that meat would remain edible if it was heated in a sealed container and the seal maintained until the meat was to be eaten (Lawrie, 1998). Heat processing is still viewed as one of the key methods for meat preservation as it kills pathogenic and spoilage microorganisms likely to grow during normal distribution and shelf life of a product while also inactivating enzymes. Heat processes for meats can be classed as sterilization or pasteurization with sterilization generally regarded as being a heat process where a product is heated to temperatures in excess of 100°C, while pasteurization is normally defined as a method of preserving food by heating it to temperatures under 100°C (typically 66–77°C). Sterilized products have a substantially reduced microbial load and as a result are shelf stable even at ambient temperatures.

From the late 1980s to late 1990s, there was considerable commercial interest in Ohmic heating as an alternative method for heat sterilization. Frampton (1988) provides a description of APV Barkers, early Ohmic sterilization systems while Sperber (1992), Rice (1995), and Giese (1996) give overviews of early commercial applications. Other scientific reviews from around this time (Sastry, 1994; Larkin and Spinak, 1996; Reznick, 1996; Zoltai and Swearingen, 1996) discuss the potential for Ohmic heating as an alternative method for sterilization. However, despite considerable potential, Ohmic sterilization has not met with much commercial success. As with any new technology there is a business risk associated with start-up costs and uncertainties in terms of market potential (Ruan et al., 2001). Another likely explanation for the lack of uptake by industry is given by Ruan et al. (2004), who state that one of the key stumbling blocks has been the greater difficulty in identifying, controlling, and validating the critical control points necessary to render a product commercially sterile under Ohmic compared to conventional (e.g., canning) conditions. This causes problems with regulatory agencies and will not

entice the food industry to consider the uptake of Ohmic heating until suitable solutions are found. Tucker (2006) stated that Ohmic heating is no longer used for ready meal sterilization in the United Kingdom.

Relative to sterilization, pasteurization is a milder heat process that kills off pathogenic organisms, but has a minimal effect on the flavor or quality of the food (Fellows, 1988). Heat pasteurization is generally used as part of a hurdle preservation strategy (Leistner, 1992) with other typical hurdles including refrigerated storage, the inclusion of antimicrobials in the product formulation (e.g., salt, nitrite, and nitrate), and modified atmosphere packaging. In recent years there has been a definite move away from sterilized ambient temperature storage products and a move toward pasteurized refrigerated products. This is particularly true in the cooked meats area with pasteurized products nowadays accounting for the vast majority of the market. Pasteurization of meat and meat products is an area where Ohmic heating has potential. Meat products are generally packaged in plastic, glass, or metal closures prior to conventional pasteurization, which is performed in a batch-wise fashion in either steam ovens or hot water immersion vessels. Under these conditions, heat transfers by conduction from the outer surface to the product interior, which leads to the outer regions of the product being at a high temperature from early on in the process while waiting for the interior to reach appropriate pasteurization temperatures. This can potentially reduce product quality and nutritional value in these regions, but can also lead to the development of a darker exterior color, which is sometimes a desirable characteristic in meat products. In contrast, Ohmic heating occurs volumetrically (i.e., heat is generated within the product volume) which largely avoids this temperature lag between the product surface and center. Due to its more rapid nature Ohmic heating makes continuous processing a reality for such products.

de Alwis and Fryer (1990) reviewed a number of early patented applications for Ohmic heating of meat products. The 17 patents they describe date from 1937 to 1975 and include commercial vending and domestic units for reheating frankfurters with only a limited number (Neumann, 1961; Luijck, 1962) designed for Ohmic heating of raw meat. Piette et al. (2001) oversaw another early investigation into the Ohmic heating of meat, which was conducted in Finland in the 1970s. These experiments involved cooking a meat emulsion while it was being pushed at a rate of a few centimeters per minute through a Teflon tube that was fitted with circular electrodes. A patent was granted but the difficulties in maintaining stable operating conditions over prolonged periods ultimately lead to this method being abandoned. Piette and Brodeur (2003) also described a French exploratory study conducted in the 1990 s between the Meat Institute Development Association and the national power corporation, Électricité de France. According to Piette and Brodeur (2003) this group developed a batch procedure for cooking 2 kg of liver pate and hams in 10 min, but the subsequent development of a prototype continuous method yielded disappointing results. More recently, Özkan et al. (2004) compared the quality of conventionally grilled hamburger patties to patties cooked Ohmically. Patties were cooked from frozen condition and these coworkers concluded that Ohmic heating was capable of producing patties of comparable quality to conventionally cooked products. In the past number of years more in-depth studies have been conducted on Ohmic cooking of meat and meat products (Piette et al., 2000a,b, 2001, 2004; Shirsat et al., 2004a–d; de Halleux et al., 2005; Zell et al., 2009a–c).

18.3.1 THE EFFECTS OF OHMIC HEATING ON MICROBIAL INACTIVATION

From the published literature it is generally believed that microbial inactivation during Ohmic heating is mainly due to thermal effects (Biss et al., 1989; Skudder, 1989; Aymerich et al., 2008). However, two other nonthermal inactivation mechanisms (chemical and mechanical) have also been proposed. Chemical inactivation has been attributed to formation of free oxygen and hydrogen, hydroxyl and hydroperoxyl radicals and metal ions, which cause bacterial death (Martin, 1960; Gilliland and Speck, 1967a,b). Mechanical inactivation has been ascribed to disruption of the microbial cell membrane leading to leakage of the cell contents (Shimida and Shimahara, 1985). Early

investigations of nonthermal inactivation mechanisms proved inconclusive due to the difficulty in eliminating thermal effects (Palaniappan et al., 1990). A study by Palaniappan et al. (1990) found no difference in the death kinetics of yeast cells between conventional and Ohmic heating. However, in more recent studies where thermal effects have been eliminated, the occurrence of mild electroporation was suggested (Cho et al., 1999; Fox et al., 2008), similar to that observed in microbes exposed to high-voltage pulses (Grahl and Maekrl, 1996), as an additional nonthermal microbial inactivation mechanism (Sastry and Barach, 2000). The effects of sub-lethal electrical treatment have been shown to reduce the subsequent thermal treatment for the inactivation of microorganisms (Palaniappan et al., 1990) and decrease the lag period in fermentation involving lactic acid bacterium (Cho et al., 1996). Hyung-Yong et al. (1999) showed Ohmic heating was more effective at killing *Bacillus subtilis* spores than conventional heating. It was attributed mainly to a thermal effect though it was suggested that the electrical current also exerts an additional effect on the germination of spores. Methods for microbial validation of Ohmic processes have been described in literature (Betts and Gaze, 1992; Parrott, 1992; Kim et al., 1996; Cho et al., 1999).

18.3.2 THE VALIDATION OF OHMIC HEATING PROTOCOLS

A key function of a heat process such as pasteurization is microbial destruction (in particular, pathogenic microorganisms). The extent to which a product has been pasteurized is dependent upon the time–temperature combination attained during heating, which can be quantified using pasteurization units (PU). In addition to its importance in microbial inactivation, a second function of meat pasteurization is to induce chemical changes in the texture, color, and flavor of the product, which are concomitant with the change from a raw to a cooked meat. Like microbial destruction, these chemical reactions are a function of heating time and temperature and can be quantified using cook value (C_s). The relationship between C_s and microbial destruction was discussed at length by Holdsworth (1985) who described four possible outcomes for a heat treatment. These outcomes redefined in the context of meat pasteurization are (a) uncooked unpasteurized, (b) cooked unpasteurized, (c) uncooked pasteurized, and (d) cooked pasteurized. For Ohmic meat pasteurization to be accepted by the industry, it must induce the chemical changes which are characteristic of a conventionally cooked product, while rendering the product safe from a microbial perspective. In addition Ohmically pasteurized products must also have comparable shelf lives to conventionally cooked meats.

Although PU and C_s give very useful information, in many cases the extent to which products are cooked by the meat industry tends not to be governed by C_s or PU values, but instead is dictated by guidelines issued by food safety regulatory authorities. In Ireland these guidelines are issued by the Food Safety Authority of Ireland and specify that the “cold spot” of a product should be heated to a temperature of $\geq 70^\circ\text{C}$ for 2 min or equivalent.

The most common method used to validate the pasteurization processes is to record time–temperature protocols from within samples during the heating process. Fiber optic probes are excellent for this purpose though they can be expensive (particularly where multiple readings are required) and are often not the most robust for commercial applications. Using normal thermocouples in an Ohmic heating environment is likely to lead to problems such as electrical discharges and signal perturbations inside the heating device. However, electrically insulated thermocouples are reliable and are a low-cost alternative to fiber optic probes. Zell et al. (2009a) described the development of a rapid response, robust, stainless steel, fully insulated triple-point thermocouple (outer diameter 2 mm, internal diameter of 1.5 mm), which had a response time of 0.6 s. Other methods that can be used to map temperatures during Ohmic heating include the use of temperature-sensitive liquid crystal sheets (Sastry and Li, 1996) or un-intrinsic chemical markers (Kim et al., 1996). Both approaches were useful but complicated and a post-process analysis was necessary to determine product temperature distribution. Other time–temperature indicators (TTI's) are described by

Tucker et al. (2002) and involve the use of microbial or chemical markers, which are placed in direct contact with the cooked food. However, it is a laborious method and is not suitable for commercial food preparation due to the addition of chemical or microbial markers. Other novel techniques include magnetic resonance imaging (MRI) (Ruan et al., 1999). MRI measurements showed very good results while being easy to use for liquid–particle mixtures. However, there are two major disadvantages; first the Ohmic heating system has to be switched off to allow measurement and second, there are lengthy data-acquisition times.

18.3.3 OHMICALLY HEATED MEAT AND MEAT PRODUCTS: QUALITY ASPECTS

18.3.3.1 Comminuted Meats

Given the more homogenous and uniform nature, it is not surprising that the majority of work published on the quality of Ohmically heated meats has focused on comminuted meats. Piette et al. (2004) and Shirsat et al. (2004c) compared the quality of Ohmically heated and conventionally cooked products. In both studies, batch Ohmic heating cells were used and an illustration of the system used by Shirsat et al. (2004c) is given in Figure 18.6a. In both studies, the sample sizes used were of similar magnitude (i.e., 1 kg), though product formulations varied from a frankfurter-style meat batter (Shirsat et al., 2004c) to a bologna sausage and a model ham (Piette et al., 2004). In addition, the steam and Ohmic cooking protocols used in these studies were broadly similar, though not directly comparable. Shirsat et al. (2004c), steam or Ohmically cooked (at voltage densities ranging from 3 to 7 V cm⁻¹) to standardized C_s values or to target end-point temperatures. Piette

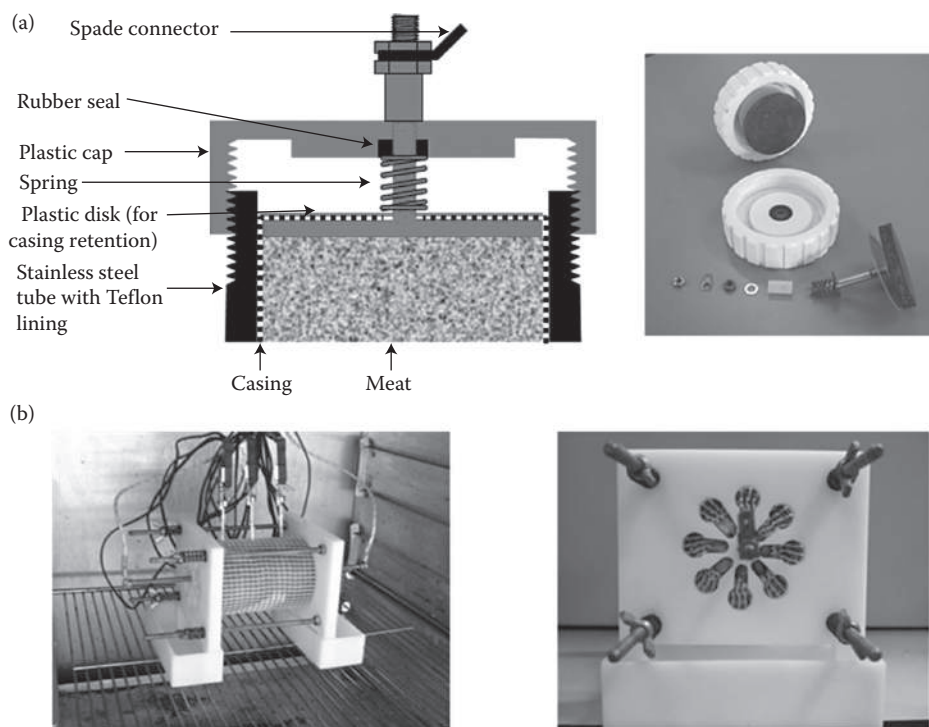


FIGURE 18.6 (a) Diagram and image of the meat cell lid showing casing sealing mechanism and electrodes. (From Shirsat, N. et al. 2004c. *European Journal of Food Research* 219: 1–5.) (b) Ohmic convection combination system showing the Ohmic heating cell in a conventional hotbox oven with a side view showing openings for hot air contact (M. Zell, personal communication).

et al. (2004), steam cooked bologna samples to an end-point temperature of 70°C while their Ohmic samples were heated to a range of target end-point temperatures (70°C, 75°C, and 80°C) at a fixed voltage density (3.5 V cm⁻¹) and also Ohmically cooked to a fixed target temperature (70°C), but varied voltage density (2.9, 3.5, and 4.7 V cm⁻¹). In addition, Piette and coworkers cooked a homogenized model ham to 70°C (at constant voltage densities of 2.3 and 4.5 V cm⁻¹) and subsequently held these samples at 70°C for 20 min. In both of these experiments, higher Ohmic voltage densities produced faster heating rates.

Texture profile analysis (TPA) of Ohmic and steam-cooked frankfurter batter by Shirsat et al. (2004c), showed no significant difference ($P \geq 0.05$) in any of the attributes assessed (hardness [1 and 2], energy [1 and 2], cohesion energy, gumminess, and chewiness) with the exception of springiness, which was significantly lower ($P < 0.05$) in Ohmically cooked samples heated to similar cook values; this trend was less pronounced in samples cooked to similar end-point temperatures. Sensory analysis on Ohmic and steam-cooked samples cooked to similar end-point temperatures supported these observations with regard to texture. In contrast, Piette et al. (2004) presented partial results of bologna TPA and found conventionally cooked samples to have higher hardness, cohesiveness, and more resilience (with no significant difference in springiness), though units for expressing cohesiveness, resilience, and springiness differ between these papers. While these researchers did not conduct formal sensory analysis, they made the observation that untrained laboratory personnel constantly referred to Ohmically cooked samples as being softer than conventionally cooked, while also noting that these personnel did not find the Ohmically heated bologna samples unpleasant. However, Piette et al. (2004) found no significant difference in TPA attributes of Ohmically heated model hams.

Instrumental color evaluations by Shirsat et al. (2004c) revealed Ohmically cooked samples (cooked both to similar cook values and end-point temperatures) differed from steam cooked in both a^* and hue angle values ($P < 0.05$) with these differences being less pronounced in samples cooked to similar cook values. Piette et al. (2004) presented L, a, and b values (but gave no results for hue angle or saturation) and also found significant differences ($P < 0.05$) in color attributes (L and a^* values) between Ohmic and conventionally cooked bologna and model ham samples, though these researchers noted these differences were small and were not likely to be detected by consumers.

Overall both papers acknowledge that subtle differences in quality could be observed in some instances in the products examined, though both come to a similar conclusion that Ohmic heating has the potential to produce the products chosen for research with comparable quality to conventionally cooked samples.

18.3.3.2 Noncomminuted Meats

Noncomminuted products account for a far greater proportion of the cooked meat market than comminuted meats. Recent work by Zell et al. (2009c) has shown it is possible to Ohmically cook whole muscle beef and produce a product with comparable quality and reduced cooking loss than conventionally cooked products. The Ohmically heated beef was found to be significantly ($P < 0.05$) more uniform, lighter and less red color, and while instrumental analysis of texture showed the Ohmically heated samples were tougher, the difference was only 5.08 N. It is also worth noting that this work (Zell et al., 2009c) was performed on an Ohmic heating system that was not fully optimized and subsequent work (M. Zell, personal communication) was performed using a novel improved Ohmic heating system design in which encased whole muscle meats (beef, ham, and turkey) were Ohmically processed in a heated chamber (set at 80°C to minimize surface heat loss (Figure 18.6b). In spite of the fact that it was an Ohmic/convection combination system, the treated products still had a lighter surface color (due to the reduced heat processing time and less associated color development). Overall however, the Ohmically treated products had more uniform color distribution with lower cook loss and no significant instrumental/sensory textural differences were noted in Ohmically heated beef, ham, and turkey products heated to comparable

end-point temperatures, though textural differences were noted in samples heated to higher (95°C) end-point temperatures.

18.3.4 THE POTENTIAL FOR COMMERCIAL SCALE OHMIC HEAT PROCESSING OF MEATS

18.3.4.1 Control of Ohmic Heating

18.3.4.1.1 Regulation of the Power Supply

Piette et al. (2004) describe a number of control options for Ohmic heaters.

1. Constant voltage: Ohmic heaters controlled in this way will show an increase in current intensity as product temperature (and therefore conductivity, Section 18.2.3.2.1) increases. Such heaters will display an increase in the heating rate during the cook cycle. This option is the simplest, but results in most of the cooking being done below optimal conditions because the chosen voltage must be limited to avoid excessive current density values toward the end of the cook cycle.
2. Constant current intensity: Operating Ohmic heaters in this manner means less voltage is required as cooking progresses, which in turn results in a decrease in the power supply and heating rate with time.
3. Constant power: Ohmic cooking at a constant power results in a virtually constant heating rate, though a slight increase in the specific heat capacity with temperature may lead to a slight decrease in the heating rate between the start and end of cooking. However, this requires more sophisticated feedback control because voltage and current intensity will vary with time.

18.3.4.1.2 Monitoring and Regulating the Extent of Ohmic Pasteurization/Cooking

The safety and shelf life of an Ohmically heated product depends on the delivery of sufficient PU, while the quality will depend on the extent of heat-induced chemical changes quantified by the C_s value. PU and C_s values cumulatively increase throughout the heating and cooling phases of cooked meat production. However, the shape of the time–temperature profiles during heating will differ substantially between conventional and Ohmically heated products. Conventional cooking is characterized by a sigmoid-shaped temperature profile which has an initial settling down period followed by a period where relatively linear temperature rise occurs and ending with a final phase where rate of temperature increase declines. In the commercial pasteurization of cooked meats, processors generally heat the cold spot in the product in excess of a target temperature for a specified time (e.g., $\geq 70^\circ\text{C}$ for 2 min or equivalent). In contrast, due to its volumetric nature, Ohmic heating is generally characterized by a relatively linear and rapid increase in product temperature. It is very unlikely that sufficient microbial inactivation or chemical changes will occur if heating is stopped and the product is cooled once it reaches the target temperature by heating in this fashion. Indeed de Halleux et al. (2005) stated that during Ohmic heating, the holding phase makes the most significant contribution to the preservation of the food and must, therefore, be increased in order to achieve a safe level of pasteurization. Therefore, to ensure that a cooked and pasteurized meat product is obtained, the following approaches could be taken. First, continue Ohmic heating the product beyond its target temperature processing until the product is sufficiently cooked and pasteurized (i.e., a form of high-temperature short time, HTST). Second, on reaching the target temperature, switch from continuous to pulsed Ohmic heating for a prescribed holding time, which could be designed to maintain a fairly stable product temperature (semi-continuous systems (Section 18.3.5). This would lend itself to very precise control because continuous feedback of C_s and/or PU could be sent to a PLC controller, which could be programmed to release products when reaching a target PU/ C_s value. And third, alternatively Ohmic heating could simply be used to preheat the product to a target temperature, before releasing the product into a chamber designed to hold the product at this temperature for sufficient time to pasteurize and cook the product.

18.3.4.2 Packaging for Ohmically Cooked Products

In commercial production of cooked meats, the majority of products are traditionally packaged in sealed casings or vacuum packaging prior to cooking. Packaging products in this way has the advantage of preventing post process contamination of the pasteurized product following cooking. Ohmic is a direct electroheating method, which means if a product is to be processed in a package, conductive regions (which could be placed in contact with a series of electrodes) will be required in the packaging to allow current to flow through the product. Nowadays, with the advances in packaging including the development of conductive polymers, there is the possibility of low-cost in-container Ohmic processing systems, which would not require aseptic conditions. Such packaging would substantially reduce the initial capital outlay associated with these systems. Recent work by Jun and Sastry (2005) modeled temperature distribution in chicken noodle soup and black beans, reheated within a flexible packaging with integrated foil electrodes. However, this work was primarily for the International Space Shuttle program and further feasibility and development work is probably needed before this could be considered for commercial application.

18.3.5 POSSIBLE PROTOCOLS FOR COMMERCIAL OHMIC HEAT PROCESSING OF MEAT

Depending on whether the product is packaged or unpackaged there are a number of possible methods for Ohmically heating meats:

Option 1: Product is left unpackaged and is Ohmically pasteurized while being continuously pumped through a tube fitted with a series of electrodes before being cooled and subsequently aseptically packaged (Figure 18.7a). This is the traditional method of Ohmically heating pumpable liquids on a continuous basis. However, of the three options this is the least likely for processing meat as it (a) will most likely be costly in terms of the initial purchase of equipment compared to conventional methods; (b) requires operators with higher skill levels to operate the aseptic packaging equipment; (c) could give rise to quality concerns as meat is traditionally cooked in a static state and continuous movement during cooking may give rise to separation within the product as fat melts and protein denatures, while movement during cooling may affect gelation; (d) could give rise to pumping difficulties as meat cooling (in which heat transfer will be primarily by conduction) will be by conventional methods that require a long cooling tube, which in turn will take up a lot of floor space.

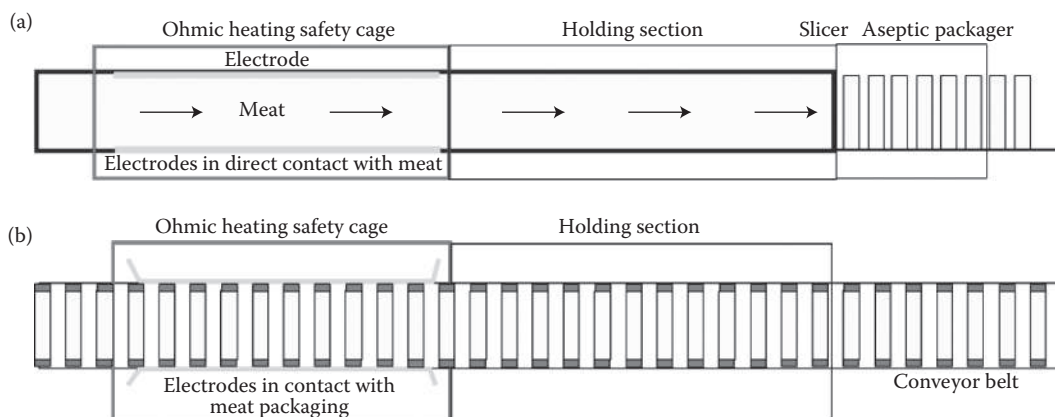


FIGURE 18.7 Illustration of continuous flow Ohmic heaters for heating (a) unpackaged meat products (b) meat products packaged in containers with conductive regions. (From Lyng, J.G. and McKenna, B.M. 2007. In: *Food Machinery Design Handbook: Farming, Processing and Packaging*, pp. 553–578. William Andrew Inc., New York.)

Option 2: The product is packaged in special packaging that includes electrically conductive regions. Electrical current is passed into the product as it passes through a continuous system similar to that described in Figure 18.7b. This is certainly a possibility but (a) depends on the availability of suitable packaging at low cost; (b) packaging design could be complex and may have to be designed on a product-by-product basis.

Option 3: The product is partially packaged during Ohmic pasteurization before being sealed under aseptic conditions following cooking. This system certainly has advantages as it could be applied in a continuous fashion similar to option 2 but (a) conventional packaging could be used and (b) the cost of creating aseptic conditions would be substantially reduced relative to the full aseptic packaging required in option 1.

A greater control of the cooking of each package could be achieved by applying options 2 and 3 above in a semicontinuous fashion where each package is Ohmically heated individually and released on reaching a target temperature, PU or C_s value.

18.3.6 OTHER DESIGN CONSIDERATIONS

Much of the modeling that has been performed to date on Ohmic heating focuses on liquids and solid–liquid mixtures. Although not carried out on meat products, a very relevant publication in the context of designing a system for Ohmic processing of a solid such as meat is the work of Marra et al. (2009), who analyzed heat transfer during batch Ohmic processing of reconstituted potato flakes. These researchers found good correlation between experimental (temperatures measured at nine different locations) and model data. They did not detect cold spots within the product; however, cold regions and heat losses were noted from the product in areas adjacent to the electrode and also the Ohmic cell structure. Subsequent work by M. Zell et al. (personal communication) has examined a range of strategies to minimize heat loss from the cell surface and electrodes. The optimum system involved the use of a combination of Ohmic and convection heating with the foodstuff contained only in a plastic casing (as illustrated in Figure 18.6b).

18.3.7 ECONOMIC ASPECTS OF OHMIC PROCESSING

Innovation, both in terms of new products and of alternative processing techniques, will be required if the food industry is to remain profitable and prosper in increasingly competitive markets. Ohmic pasteurization offers potential economic and practical benefits to the meat industry, which could possibly include increased energy efficiencies, increased throughput potential for continuous vs. batch processes. The basic energy balance formula governing pasteurization is given in Equation 18.4

$$Py = \frac{mC(\Delta T)}{t_p} = \frac{H}{t_p} \quad (18.4)$$

where P is the power consumption of cooker (kW); ψ the efficiency of cooker; m the mass of meat (kg); C is the specific heat capacity of the meat ($\text{kJ kg}^{-1}\text{°C}^{-1}$); ΔT the temperature rise in meat during cooking (°C); H the energy required to cook the meat (kJ) and t_p is the duration of the heating process(es). Both conventional and Ohmic pasteurization require the same energy input to heat a specified mass of an identical product. However, Ohmic heating is generally regarded as being a more efficient power source than conventional methods, with energy efficiencies of greater than 90% being reported (de Halleux et al., 2005). Therefore, all things being equal, Ohmic heating will require less power input than conventional cooking for a given temperature rise. It has been reported that Ohmic cooking can reduce energy consumption by 82–97% compared to conventional smoke-house cooking (de Halleux et al., 2005) while meeting the minimum specifications necessary for pasteurization. In addition to improved energy efficiencies, the potential for increased throughput

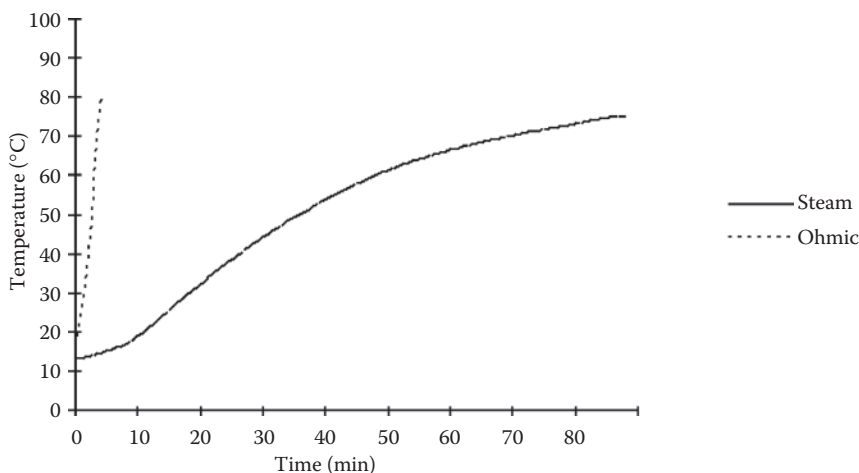


FIGURE 18.8 Time vs. temperature profile for steam and Ohmically (5 V cm^{-1}) cooked 1 kg meat emulsions. (From Lyng, J.G. and McKenna, B.M. 2007. In: *Food Machinery Design Handbook: Farming, Processing and Packaging*, pp. 553–578. William Andrew Inc., New York.)

and reduced t_p is illustrated in Figure 18.8, which shows the substantial reduction in time taken to reach pasteurization temperatures in meat emulsion samples.

18.4 OHMIC HEATING IN FISH AND FISH SURIMI PROCESSING

In comparison to meat and meat products, considerably less research has been performed on Ohmic heating of fish, although it would be expected that many of the findings for meat and meat products would show similar outcomes in fish. Some of the published works on fish are review articles that mention Ohmic heating (amongst other methods) as potential heating methods for fish and fish products (Perez-Mateos and Borderias, 1997). However, Matsubara et al. (2007) looked at Ohmic heating as a method for improving the quality of salted-dried salmon. In their work, Ohmic heating was incorporated into the traditional salting and drying process. These workers found that heating the salmon to 45°C for 5 min prior to salting had a significant lowering effect on texture as assessed by the texture profile analysis characteristics—hardness and cohesiveness—which had the effect of making the salted and dried salmon more fragile. Furthermore, myotomal blocks in the finished salmon muscle were detached at the connective tissue regions after Ohmic heating. This, together with a decrease in the amount of salt-soluble protein with no change in the water-soluble protein substantially increased the acceptability of the product. Similar effects were found when a number of meat slices were Ohmically heated in a carrier solution containing 0.5% NaCl.

AbuDagga and Kolbe (2000) studied and modeled the Ohmic heating of surimi paste produced from Pacific whiting. Ohmic heating at a high-voltage gradient (120 V cm^{-1}), not unexpectedly resulted in a heating rate which was 11 times higher than that of conventional heating for a cylindrical sample of 19 mm diameter. More importantly, the time during which the center of the sample remained within the critical enzyme activity range was significantly reduced. In addition, the effects of voltage gradients across the sample, moisture content, electrode design, and heat exchange with the surroundings were also investigated. This latter heat leakage to the surroundings significantly lowered the heating rate near the sample surface. The same team (Yongsawatdigul et al., 1995a) found that Ohmic heating also improved the gel functionality of this surimi. Yongsawatdigul et al. (1995b) investigated the electrical conductivity of the surimi paste. Similar to previously discussed

observations in meat, the electrical conductivity of the paste increased with temperature and salt content and slightly increased with moisture content, while it was well correlated linearly with temperature. The voltage gradient did not affect conductivity while variations with the voltage gradient observed in surimi containing 3–4% salt, were probably caused by electrochemical reactions at electrode surfaces. Finally, Zhao et al. (1999) studied the corrosion of stainless-steel electrodes during the surimi heating. Electrode polarization and corrosion is a potentially serious inhibitor to the wide scale application of Ohmic heating. It was reported that the electrolytic reaction observed at the electrodes below 500 Hz and 3000 A m² had disappeared when frequency was increased to 5000 Hz and higher, at current densities of 2300 A m². Several studies looked at the quality of the surimi paste thus processed. Panida et al. (2007) studied the texture, colour and microstructure of Ohmically heated surimi seafood gels. Gel properties were affected by the type of additive, concentration, and cooking method. Starch had a more pronounced effect on gel texture at low concentrations with potato starch giving an improved gel strength compared to wheat starch. However, potato starch decreased the gel whiteness. Non-fish protein additives gave equal or improved texture to the gels as did fish protein additives but there was deterioration in gel colour. In general, Ohmic cooking with its rapid heating gave improved gel strength over conventional methods. A similar exercise was conducted by Sung et al. (1995) on kamaboko (fish protein gel) made from minced Alaska pollack. Samples containing additional NaCl (0–1 w w⁻¹%) and/or starch (0–10 w w⁻¹%) were heated to 90°C with an alternating current (0–20 V) at various frequencies (50 Hz–10 kHz). Breaking strength, color, and structure were examined. The samples, which had heating rates of 7.5 times that of conventional boiled samples, were similar in color, but had breaking strengths 1.6 times that of the boiled samples. Results suggest that water is individually separated in the protein gel matrix, and that the gel has a maximum dielectric constant (ϵ') at a frequency dictated by gel structure and component distribution.

Another application has been suggested for Ohmic heating in the production of surimi production in the area of protein coagulation/denaturation in wastewater. Wastewater from this process can contain relatively high levels of protein that contribute to a high biological oxygen demand (BOD) of the water, which requires long treatment time and large storage capacity when treated by traditional methods. Kanjanapongkul et al. (2009) described the construction of a laboratory scale Ohmic heating system, which was capable of heating the wastewater to a sufficient temperature (60–70°C) to coagulate the protein (which could then be removed by centrifugation), thus, reducing the BOD of the wastewater.

Also in the area of surimi processing, another application that has been proposed has been the purification of enzymes. In general, high molecular weight proteins are more susceptible to heating (Cheng and Parrish, 1979). Ohmic heating has been used to coagulate fish proteins and partially purify proteolytic enzymes in surimi wash water prior to membrane filtration. Fish muscle is a rich source of proteinases such as cathepsins, which have many industrial applications. Benjakul et al. (1978) found that in a processing sequence, which included ultra filtration and freeze drying, a mild Ohmic heating protocol (55°C for 3 min at 90 V) was the most efficient step for concentrating the proteinase.

18.5 OTHER POTENTIAL COMMERCIAL OHMIC HEATING APPLICATIONS FOR MUSCLE FOODS

18.5.1 DEFROSTING MEAT AND FISH

Defrosting a product involves increasing its temperature from frozen storage temperatures to just below (i.e., tempering) or above (i.e., thawing) its freezing point. In commercial practice, conduction-based systems are the most commonly used and involve the supply of heat to the outer product surfaces (via air, water, contact with a heated surface, or condensing steam [vacuum-thawing]) with this heat then being transferred to the center of the product by conduction. However, a

number of studies have evaluated the potential for Ohmic defrosting of meats. One of the difficulties with using Ohmic heating for defrosting is that for heat to generate, direct contact between electrodes and product surface must occur. However, the solid nonpliable nature of frozen foods could pose problems in this regard. Yun et al. (1998) integrated two electrodes into an immersion vessel with the aim of combining Ohmic (0–210 V AC at frequencies between 60 Hz and 60 kHz) with conventional water immersion (10 or 20°C) for thawing frozen chunks (10 cm³) of meat. Under these conditions no direct contact between the meat and the electrodes occurred. Thawing time was reduced with increasing voltage, though frequency changes had no significant affect. Samples treated at lower voltages showed reduced drip loss and improved water-holding capacity. Hong et al. (2007) compared brine immersion and electrode contact Ohmic thawing methods for pork meat and found more rapid thawing with the electrode contact method, while the total color difference was slightly higher with the Ohmic immersion thawing. Increasing voltage increased water-holding capacity and generally tended to decrease TBARS values. Overall, the immersion thawing proved more suitable at high-voltage levels, while electrode contact was more suited to low-voltage levels. Products such as patties have flatter surfaces than other meats. Kim et al. (2006) Ohmically thawed frozen pork patties formulated with 0% and 0.5% added salt. The thawing rate increased with increasing power intensity while patties with added salt thawed faster than those without. Increasing the power intensity tended to increase the TBARS and it was suggested that thawing at 50 V induced lipid oxidation in pork patties.

Roberts et al. (1998) designed a prototype Ohmic thawing unit with surface temperature sensing and automated control for thawing two shrimp blocks simultaneously. The substantial amount of wastewater, generated with conventional warm water immersion thawing is avoided using Ohmic heating, which is also more energy efficient. The design features of the system prevented runaway heating. A subsequent comparison of the sensory, microbial, and quality attributes of shrimp thawed by conventional water immersion vs. Ohmic methods (Roberts et al., 2002) revealed no significant differences in sensory or total aerobic microbial counts, while small shrimp had higher moisture content when conventionally thawed. Overall the team concluded that Ohmic thawing is effective for shrimp blocks.

Miao et al. (2007) compared the thawing rate and gel strength in frozen surimi in saline cubes thawed by conventional and Ohmic methods. The researchers found faster thawing rates and stronger gels in the Ohmically thawed product. Homogenous temperature distributions were obtained when the saline solution concentration was <4% with 20 V applied voltage and a frequency of 60 Hz.

18.6 CONCLUSION

The majority of recent work on Ohmic processing of muscle foods has focused on the pasteurization of meat and meat products, although work has also been performed on fish, particularly in the area of surimi processing. Given the positive benefits Ohmic technology has shown in these areas, it is important to continue research in these fields to ensure a strong foundation of technical knowledge, which is available to assist in commercial uptake and system development, though demand for commercial processing systems will only arise by creating an awareness in the industry of its applications and the potential benefits in processing muscle foods.

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NOMENCLATURE

a	redness/greenness (Hunter Lab scale)
b	yellowness/blueness (Hunter Lab scale)
BOD	biological oxygen demand
C	specific heat capacity ($\text{kJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$)
C_s	cook value
E	electrical field strength (V cm^{-1})
ϵ'	dielectric constant
ϵ''	dielectric loss
f	frequency (Hz)
H	energy required to heat the muscle food (kJ)
J	current density (A m^{-2})
I	amperage (amperes, A)
L	lightness (Hunter Lab scale)
m	mass of muscle food (kg)
P	power consumption of cooker (kW)
PU	pasteurization units
Q	heat generation rate per unit volume (W m^{-3})
ρ	density of the material (kg m^{-3}).
R	resistance (ohms, Ω)
t_p	total cooking time (s)
TPA	textural profile analysis
TBARS	thiobarbituric acid reactive substances
V	voltage (V)
	electrical conductivity (S m^{-1})
ΔT	temperature rise in meat during cooking ($^\circ\text{C}$)
Λ	resistivity ($\Omega \text{ m}$)
ψ	efficiency of cooker

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19 Applications of Ohmic Heating to Milk and Dairy Products

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19.1 INTRODUCTION

Ohmic heating is used for thermal preservation of food, that uses the passage of an alternating electric current through the food material, where the latter serves as an electrical resistor and it results in release of heat. The instrumental design is made up of electrodes in contact with the food material, where electrodes pass electricity through the food material using a variety of voltage and current combinations. Electrical energy is dissipated into heat that results in rapid and uniform heating without any use of hot heat-transfer surfaces. Ohmic heating is also termed “electrical resistance heating,” “Joule heating,” or “electro-heating,” and can be used for variety of applications in the food industry.

Fluid and semi-fluid foods such as milk and eggs are considered one of the best candidates for Ohmic heating (Pereira et al., 2007). Milk is composed of water (87.3%), milk fat (3.7%), lactose (4.6%), protein (3.25%), mineral substances (0.65%), organic acids (0.18%), and miscellaneous substances (0.14%). It provides significant amounts of proteins and most micronutrients including calcium, B vitamins, vitamin A, iodine, magnesium, phosphorus, potassium, and zinc. The nutritional benefits of milk make it an important source of nutrients in daily diets. It helps to improve the bone and dental health, and reduce blood pressure; therefore it prevents dental caries, osteoporosis, and hypertension. The calcium in milk products aids in reducing the risk of colon cancer (Wells, 2001). Apart from its nutritional benefits, the flavor of milk and milk products is relished throughout the world. The flavor quality of milk becomes a key parameter of product quality, as acceptance is largely dependent on flavor. Since fresh milk has a very delicate flavor; any off-balance of the

flavor profile can emerge into “off-flavor” which can be easily detected by the consumer. The flavor composition of milk is complex; at least 400 volatile compounds have been reported in milk, covering a wide range of chemical classes including lactones, acids, esters, ketones, aldehydes, alcohols, furans, carbonyls, pyrazines, sulfur compounds, and aliphatic and aromatic hydrocarbons (Moid et al., 1994). The off balance of these volatile compounds in milk, as well as the generation of some new “off-flavor” compounds, can cause off-flavor in milk.

Thermal processing is the most established method to achieve microbial safety and shelf life stability of milk. HTST pasteurization is mostly used method, but shelf life of the final product is only 14–20 days at refrigeration temperature and it can impart a slight cooked and sulfurous flavor to the milk. Ultra-high-temperature processing (UHT) is another widely used milk sterilization technique; it is mainly employed by heating milk at 138–150°C for small time period (normally hold for 1–2 s), which is the temperature required to kill spores in milk (He, 2012). UHT process can affect taste and texture due to development of new volatile compounds. The promising nonthermal methods including membrane filtration, high-pressure processing (HPP), pulsed electric field treatment and Ohmic heating are used to achieve a microbial shelf life similar to that of UHT milk and to minimize the generation of off-flavor compounds. Ohmic heating is one of better process as it causes rapid heating without any use of hot surface.

19.2 THE HISTORY OF OHMIC HEATING APPLICATIONS TOWARD MILK

Pasteurization of milk by Ohmic heating was first introduced in the United States during 1920s. Initially the pasteurization was done by passing the milk through parallel plates under the influence of voltage (Anderson and Finkelstein, 1919). This technology nearly disappeared in 1950s due to lack of the suitable inert electrode material and improper contact between electrodes and the food product (De Alwis and Fryer, 1990). Now, due to improved materials and designs for Ohmic heating, one of the biggest achievements for this technology was the continuous-flow Ohmic heater (Skudder, 1988; Amatore et al., 1998; Berthou and Aussudre, 2000). This was followed by considerable amount of attention towards using Ohmic heating for aseptic processing of liquid and liquid-particulate foods.

19.3 PRINCIPLE OF OHMIC HEATING

Electrically conductive moist food materials are perfect candidates for Ohmic heating. For example, milk, because it contains water and ionic salts and is capable of conducting electricity. With the passage of electricity through milk, the resistance causes heat generation that ultimately causes pasteurization. The heating rate has a direct relationship to the square of the electric field strength and the electrical conductivity. The electric field strength is controlled by adjusting the electrode gap or the applied voltage. However, the heating rate depends largely on the physical characteristics of the food itself, especially on the electrical conductivity (De Alwis and Fryer, 1990).

19.4 APPLICATIONS OF OHMIC HEATING FOR PROCESSING OF DAIRY FOODS

Ohmic heating systems can be adapted to various aseptic food-processing lines (Kim et al., 1996). The UHT processing can be easily achieved using Ohmic heating and the shelf life can be increased without any use of cold chain storage (Biss et al., 1989). It requires precise process control. Ohmic heating can be used to reach prescribed temperature in shorter time than conventional heating. The short processing time decreases the adverse effects of heating on the quality characteristics of food. It can be used to heat food products in rapid and uniform manner leading to less aggressive thermal treatment, it can cause pasteurization of the proteinaceous foods without coagulation such as liquid egg and whey (Icier and Bozkurt, 2010; Icier, 2010). Since the degradation of proteins and fouling in the equipment surfaces during Ohmic heating is less, compared to conventional heating methods,

so the clean-up and maintenance costs are lower as well (Tempest, 1992; Reznick, 1996). There is no need for the mixing of fluid foods for homogenous heating, which is important for foods sensitive to mechanical damage. Power supply units are not complex when performed at low frequencies. Energy conversion efficiencies are very high; systems have small equipment footprints, and are generally quiet. Accurate temperature control is possible with instant on/off control (Tempest, 1992; Reznick, 1996).

There are many benefits of using this technology in food processing; however, there are still problems that occur in Ohmic heating systems. The system demands proper electrical insulation, accurate process control systems, and well-trained personnel for continuous operation and maintenance. The industrial applications are limited due to consumer constraints to electrically processed products; hence there is no available data on the effects of Ohmic heating on formation of some toxicological and mutagenic substances, and precise information on assurance of its lethality in various kinds of foods. Furthermore, the cost of commercial Ohmic heating systems is a huge investment for a manufacturing facility, and can be in excess of \$9,000,000 USD (Anderson, 2008). However, its processing costs are comparable to commercial conventional pasteurizing systems.

The full commercialization of Ohmic heating technology depends in part on the development of adequate safety and quality-assurance protocols in order to obtain an approved filing of the process with the FDA for all possible food materials (Ye et al., 2003).

Products with high thermal conductivity like dairy products, custards, desserts, and fruits with their values ranging from 0.1 to 0.5 S m⁻¹ are very good candidates for Ohmic heating. Across this group, very fast heating, up to 840°C s⁻¹, is possible, but to realize the full potential of rapid heating, it should also be possible to cool rapidly otherwise thermal degradation will occur in the cooling cycle. Rapid cooling of homogeneous fluids like milk is not a problem. It was found that by raising temperature of milk from 100°C to 150°C and back to 100°C in 1 s with Ohmic heating, a marked improvement in taste can occur compared with that of conventional long-life milk produced in plate-type heat exchangers operating at around 140°C with longer process times. The aim is therefore to produce long-life milk needing no refrigeration, and with the taste qualities associated with pasteurized bottled milk (Stirling, 1987).

Development of new technologies for continuous thermal food treatment are still of great industrial and scientific interests. Ohmic heating is one of these food-processing technologies, consisting of direct passage of electric current through the product. However most of the studies were centered on the sterilization of food products containing particles (De Alwis and Fryer, 1990; Fryer et al., 1993; Wadad et al., 1996; Sudhir et al., 1998; Benabderrahmane and Pain, 2000; Eliot-Godéreaux, 2001) and continuous food-fluid treatment was the focus of very few studies (Marcotte, 1999).

Beattie (1914) used a resistive heating method for infant milk pasteurization, which was followed by Anderson and Finkelstein (De Alwis and Fryer, 1990) who used it for sterilized milk with parallel walls of graphite across which a set voltage was applied. These experiments allowed the electro-pure process to be used industrially in the 1930s. Later in 1987, a 50 kW transverse-mode Ohmic heater was used in combination with a standard plate-type regenerative cooler (Stirling, 1987). The electrodes are parallel, slightly spaced between plastic insulating spacers and channeled internally to fluid flow. As the surface in contact with the product is large and the voltage between the electrodes is low (96 V), the current is high and results in overheating, boiling, and electrode erosion. Due to this reason, its application is restricted to fluids without particles such as milk and beverages (Prescott, 1927).

19.5 FOULING

Fouling is a major issue in heat exchangers and it still exists for number of food products. Ohmic heating is well known to minimize the fouling phenomenon as it heats the product by admitting the current directly in the product. This technology can act as a good alternative to conventional processing, especially for pasteurizing or sterilizing dairy desserts known for generating large amount of soil on heated surfaces.

Fouling of equipment during processing especially in the dairy industry is a big issue in the North American food industry. In addition to the cost of effluent disposal, a large amount of money could be added due to plant shut down for cleaning. In case of indirect heat-transfer technologies (plate heat exchangers, tube heat exchangers) the presence of a fouling layer dramatically decreases the thermal performance hence increases the fouling phenomenon.

19.6 FACTORS RESPONSIBLE FOR FOULING OF MILK DURING OHMIC HEATING

Fouling is a big issue in conventional heating of milk and milk products. Deposition is dependent on a number of stages beginning from denaturation and aggregation of proteins followed by transportation of the aggregated proteins to heat-transfer surface, which will result in merging of these proteins into deposit layer. The latter is subjected to hydrodynamic forces and it could result in a possible re-entrainment or removal of the deposits (Sun et al., 2008).

It was found that deposit creation on electrodes is pertinent to the problem of the electrodes corrosion. The corrosion of electrodes can be eliminated by using higher frequencies (10 kHz) from a pulsed power supply. Fouling of milk was studied by Ayadi et al. (2004b). Although the mechanism and reactions between all milk components are not yet fully understood, a relationship has been described between the denaturation of native β -lacto globulin and fouling of heat exchangers (Toyoda, 1994). The rate of the denaturation and agglomeration of proteins and fouling is dependent upon on following factors:

- a. *Temperature and composition of milk:* During high-temperature processing of milk, fouling and deposit of proteins and minerals on the surface of the heat exchangers is a common phenomenon. High temperature and milk suspensions are major problems responsible for fouling of heat exchanger because it reduces heat-transfer efficiency and increases pressure drop and hence affects the economy of a processing plant. As a result of fouling, there is a possibility of deterioration of the product quality because the process fluid cannot be heated to the required temperature for pasteurization (Ayadi et al., 2004a).
- b. *Micro-layer formation:* Primary micro-layer formation on electrodes can be due to oxidation or reduction reactions. Electrochemical reactions in the system electrode and electrolyte (redox reactions and electrochemical corrosion processes) start immediately after the power supply is connected. This layer forms a part of electric circuit as an additional electric resistance.
- c. *Electrode type:* Appropriate electrode material can be used to effectively inhibit undesirable electrochemical phenomena. Samaranayake and Sastry (2005) worked on understanding the electrochemical behavior of following electrode materials: titanium, stainless steel, platinized-titanium, and graphite at varying pH range of 3.5, 5.0, and 6.5. 60 Hz sinusoidal alternating current was used for examination of electrodes. The results highlight the relatively inert electrochemical behavior of platinized-titanium electrodes at all the pH values.
- d. *Corrosion:* Corrosion or decaying of electrodes can cause shortening of electrodes life time and contamination of food (Perchonok and Bourland, 2002).
- e. *Movement of electrodes:* Monitoring of movement of gas bubbles in closed environment of a transit vehicle in a planetary base is required. If gas bubbles have no preferred direction of movement in a microgravity environment, gas blanket could develop over the electrodes and heating can stop altogether.
- f. *Product composition:* The calcium ions present in milk enhance the deposition by forming bridges between the proteins adsorbed on the heat-transfer surface and aggregates formed in the bulk by influencing the denaturation temperature of β -lactoglobulin, and promoting aggregation by attaching to β -lactoglobulin (Xiong, 1992; Changani et al., 1997; Christian et al., 2002).

g. *pH*: pH decrease will also cause an increase in concentration of ionic calcium due to dissolution of calcium phosphate from casein micelle and its increased solubility (Lewis and Heppell, 2000).

19.7 EFFECTS OF OHMIC HEATING ON QUALITY CHARACTERISTICS OF MILK AND MILK PRODUCTS

The quality parameters concerning liquid food products, such as heat-sensitive compounds, inactivation of microorganisms and enzymes and physical characteristics, play an important role in the industry. In the following subsections, as well as changes in proteins, free fatty acids, rheological, and microbial properties during Ohmic heating are discussed in detail.

19.7.1 PROTEINS

Ohmic heating is known for not causing any changes in structure/quality of proteins. Castro et al. (2004) hypothesized that there is additional effect of the electric field, which causes the separation of the protein structures (enzyme molecule). They checked this impact by using polyacrylamide gel electrophoresis (PAGE) with proteins in their native form (native PAGE). The proteins moved through the gel when an electric field was applied and each band on the gel represented a different protein (or a protein subunit). If heating causes any subunit separation, different bands would have appeared in the gel, which corresponds to different subunits.

However, both the untreated and treated sample (in this latter case, enzymes used were both conventionally and Ohmically treated) presented the same number and position of bands in the gel. This led to the conclusion that the enzyme had the same molecular weight and no subunit separation occurred before or after the thermal treatments (conventional or Ohmic). On the contrary, Ohmic heating has a tendency to cause fouling for dairy products. This fouling was specifically found in the case of high proteinaceous liquid when processed at high temperature or high solute concentrations (Ayadi et al., 2004a).

Ayadi et al. (2004b) used model fluid solutions of whey protein and xanthan gum based on the fact that the milk deposit formation is caused at temperature above 75°C by thermal denaturation of β -lactoglobulin and xanthan gum can modify the viscosity of the model fluid as a dairy product. It was found that pressure drop could decrease rapidly when channels are blocked by deposit and there can be decrease in overall heat-transfer coefficient as the fouling layer is formed on heat-transfer surfaces. By changing the inlet design and optimizing the flow field in the channels of Ohmic cells, the deposit and the fouling ability in laminar region can be decreased.

19.7.2 CHEMICAL PROPERTIES

Ohmic heating can be used to process products with much alteration in chemical properties of milk and other dairy products. Ohmic heating reduces the problem of fouling and thermal damage to the product. It will result in superior quality product with minimal changes in nutritional, structural, and organoleptic changes and that too it can be manufactured in a short operating time. This technique has a potential to be used in blanching, evaporation, dehydration, and fermentation (Castro et al., 2004).

It was found that Ohmically heated goat milk has same chemical properties to that of conventional heating. In goat milk samples treated by Ohmic heating, the titratable acidity 0.12% (as lactic acid), pH value 6.59, and total fatty acids content in milk fat 86.5 g 100 g⁻¹ were comparable to those found in milk treated by conventional process (Pereira et al., 2006).

It was found that Ohmic heating does not promote more free fatty acids (FFA) release than conventional heating. Rancid flavor in milk is commonly associated with excessive accumulation of free fatty acids in milk which is caused by disruption of the milk fat globule membrane. Pereira et al. (2007) found the impact of conventional thermal and Ohmic heating on disruption of milk

fat globule membrane. Solid-phase micro-extraction and gas chromatography methods were used in the quantification of individual free fatty acids in dairy products, which gives enough information to detect levels of rancidity in milk. This disruption can result in a release of higher amount of medium- and short-chain fatty acids, which can cause rancidity. Similarly they passed this milk solution through pumps and heat exchangers but it was found that Ohmic heating at 72°C/15 s does not promote higher free fatty acid release than conventional heating.

19.7.3 RHEOLOGICAL PROPERTIES

Evaluation of rheological properties of liquid foods during Ohmic heating is very important for designing continuous Ohmic heating units. The rheological changes of reconstituted whey solutions during Ohmic heating were observed by Icier (2009). It was found that by increasing the extent of thermal treatment by both Ohmic and water-bath heating methods, the consistency coefficient of whey solutions was found to be decreasing. The voltage gradient was not important ($p < 0.01$) statistically, while the solute concentration and its interaction with temperature were effective on the consistency coefficient. With increase in temperature, consistency coefficient was found to be decreasing and on other hand, flow behavior index “ n ” was found to be increasing with increasing temperature, and decreasing with increasing concentration.

When the processing of whey solutions was done by Ohmic methods, it was found that rheological properties were time dependent in the temperature range of 20–80°C. The solutions did not have any yield stress values for the solute concentrations below 24%. Thermal history of conventional heating was matched to Ohmic heating at 20 V/cm to determine the possible electrical effect of Ohmic heating on rheological properties. Activation energies for the temperature dependency of the consistency coefficient were in the range of 26.34–45.79 kJ/mol for Ohmic heating, and 26.70–50.04 kJ/mol for conventional heating. Reconstituted whey solutions were less sensitive to temperature changes during Ohmic heating. It is a fact that lower solute concentrations had lower activation energies during Ohmic heating than conventional heating. The most probable reason for decreased sensitivity is due to electrical effects of Ohmic heating which causes a decrease in consistency while on the contrary, thermal effects causes increase in the consistency. It was found that fast heating causes delay in processes like gelation and degradation, and it enhances the occurrence of reaction products resulting in rupture of chemical bonds which in turn causes the decrease in consistency. On the contrary, there could be a decline in the consistency of the bulk fluid due to electrochemical reactions and the fouling which occurs on the electrodes of the Ohmic heater. In further studies, micro-scale investigations of changes in structure of milk products due to electrical effects of Ohmic heating are required.

19.7.4 MICROBIAL STUDIES

Owing to its high water activity, milk serves as an excellent culture medium for the growth and multiplication of many kinds of microorganisms, which frequently contaminate dairy products during unsanitary manufacturing conditions. The effectiveness of Ohmic heating has been credited to rapid and uniform heating alone, with no consideration to additional nonthermal effects of electricity (Castro et al., 2004). However, on other hand, literature also suggests that additional lethal non-thermal effects are highly significant. This approach to food processing brings in the opportunity for significant process time reduction, adding to the advantages of Ohmic heating.

Palaniappan et al. (1990) reviewed the literature available at that time on the effect of electricity on microorganisms and concluded that much of the evidence was inconclusive. Lack of adequate temperature control within experiments was one of major obstacle in interpreting experimental data; thus it was not possible to finalize whether a given effect was due to thermal or electrical effects. Thereafter, it has been strongly recommended that studies related to study electrical effects ensure that control samples would be treated with the same thermal history as Ohmically processed samples. This was a difficult task, but was accomplished by further researches, which are explained in the following sections.

Palaniappan et al. (1992) studied the death kinetics of yeast cells (*Zygosaccharomyces bacilii*) under conventional and Ohmic heating, and found no difference in the death rate. However, pre-treatment by Ohmic heating at specific temperatures caused a significant decrease in the succeeding death times of *Escherichia coli* cells. This study was conducted using identical temperature profile for both Ohmic and conventional heat treatments. However, in more recent studies, it was found that thermal death times decreased significantly under Ohmic heating conditions. Pereira et al. (2007) studied inactivation kinetics of *E. coli* in goat's milk during Ohmic and conventional heating under identical temperature, and found that the thermal death times were shortened under Ohmic heating.

Yoon et al. (2002) found that intracellular material from *Saccharomyces cerevisiae* was exuded during Ohmic heating when field strengths ranging from 10 to 20 V/cm were used. Field strength and frequency were found to cause increase in exudation. It was found that cell damage induced by Ohmic heating was due to electroporation which causes fatal damage to cell membranes. Sun et al. (2006) used conventional and combination (sub lethal Ohmic + conventional) treatments to study the death rates of *Streptococcus thermophilus* in milk. Microbial analysis was done by conventional thermal processing of samples that were compared with combination treatments (Ohmically heating samples from 10°C (50°F) to 42°C (108°F) for 12 successive cycles followed by the thermal processing in same conditions as the conventionally thermal treated samples were done). Inactivation of *S. thermophilus* was significantly enhanced by the combination treatment, which suggests a nonthermal effect of electricity.

Very low electric fields of 1–2 V/cm have been observed to influence bacterial cells during cooling action. Subsequently, Loghavi et al. (2007, 2008) have not only confirmed these results, but also have shown the sensitive influence of waveforms and frequency. These studies show that mild electric fields have significant effects on cells and can help in additional microbial inactivation.

Pereira et al. (2007) compared the impact of Ohmic heating and conventional heating on the death kinetic parameters of *E. coli* ATCC 25922 in goat milk. The goat milk samples were heated up to 90°C using four different field strengths ranging from 20 to 54 V cm⁻¹ with a 2 cm gap between electrodes. For Ohmic heating assays, approx. 25 mL of the inoculated sample was treated at 55°C, 60°C, 63°C, and 65°C. Possible nonthermal effects of the Ohmic heating caused by chemical reactions at the surface of electrodes were avoided by the use of platinized titanium electrodes, which are relatively inert applying commonly available low-frequency alternating currents in the whole range of pH values. For the experiments with conventional heating the inoculated samples were homogenized and subjected to the test temperatures of 55°C, 63°C, 65°C, 67°C, and 70°C in a temperature-controlled water bath (Table 19.1).

TABLE 19.1

***D* and *z* Values for *Escherichia coli* Cells Inactivation When Submitted to Conventional and Ohmic Heating**

Temperature (°C)	Conventional Heating			Ohmic Heating		
	<i>D</i> (min)	<i>z</i> (°C)	<i>r</i> ²	<i>D</i> (min)	<i>z</i> (°C)	<i>r</i> ²
55	10.9 ± 108	23.1	0.98	14.2 ± 0.2	8.4	0.99
60				4.2 ± 0.6		
63	3.9 ± 0.5			1.9		
65	3.5 ± 0.2			0.86		
67	2.8					
75	1.5					

Source: From Pereira, R. et al. 2007. *Chemical Papers*, 61(2), 121–126. With permission.

The z value for conventionally heated samples contaminated with cells of *E. coli* was substantially higher ($z = 23.1^{\circ}\text{C}$) than that obtained for samples treated by the Ohmic heating ($z = 8.2^{\circ}\text{C}$) (Table 19.1). Therefore, noticeable additional killing effect of the electrical current on *E. coli* was observed at almost all temperatures studied.

Further work is needed to investigate the possible different effects of electrical treatments on the quality, nutritional properties, chemical structure, and functional properties of the dairy products compared to conventional heating methods.

19.8 EGG PRODUCTS

Characterization of the flow characteristics of liquid whole egg are vital for modeling, design and scale up of the continuous Ohmic heating systems for pasteurization of liquid egg and its products due to high protein content and fouling problem. Thermal pasteurization is a big issue in eggs due to its instability in the range of efficient pasteurization temperatures (Geveke, 2008).

Icier and Bozkurt (2010) analyzed the rheological behavior of the Ohmically heated liquid whole egg in the temperature range of 4–60°C. Power-law characteristics were represented during Ohmic heating of liquid whole egg since either regression coefficients of power law equation were comparatively higher or both x^2 and RMSE (root mean square errors) values were comparatively lower than Newtonian-type equation for range of temperatures studied. For liquid whole egg, the flow behavior index (n) varied in the range of 0.86–0.90 varying according to temperature. Liquid whole egg indicated presence of protein denaturation, when heated at 60°C using Ohmic heating by exhibiting a higher degree of thixotropic index (38.53 Pa s⁻¹).

Denaturation was indicated by ascending and descending curves in the thixotropic cycle as dependent on the direction of shear negligible orientation (Figures 19.1 and 19.2). With decrease in temperature, thixotropic index was decreased as it was 5.44 and 14.89 Pa s for 4 and 10°C, respectively. Hence, it was found that less denaturation occurs below the pasteurization temperature.

Degradation of functional properties of egg products like coagulation, foaming, and emulsifying properties and product quality was found with conventional thermal pasteurization which is most widely used technique (Nolsoe and Undeland 2009). Ohmic heating can be used as an alternative method for processing liquid egg product commercially, due to plenty of information available on the change of rheological properties and fluid dynamics characteristics of Ohmically heated liquid whole egg in the literature.

The rheological properties were influenced by composition of liquid egg and their behavior was changing with processing temperatures. At temperatures above 60°C, liquid egg showed a pseudo plastic behavior (Hamid-Samimi et al., 1984; Hamid-Samimi and Swartzel, 1985).

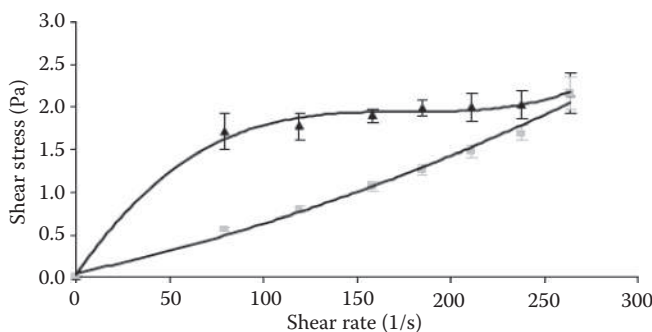


FIGURE 19.1 Thixotropic behavior of whole liquid egg at 60°C during Ohmic heating; ▲, Up term; □, Down term. (With kind permission from Springer Science + Business Media: *Food Bioprocess Technology*, Ohmic heating of liquid whole egg: Rheological behaviour and fluid dynamics, 4(7), 2009, 1253–1263, Icier, F. and Bozkurt, H.)

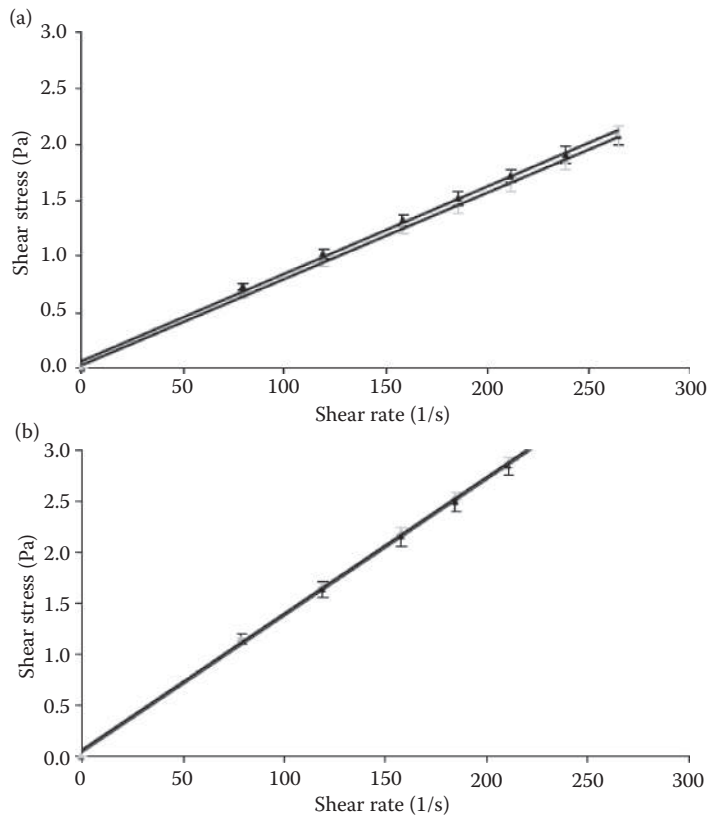


FIGURE 19.2 Thixotropic behavior of liquid whole egg at storage conditions: (a) 20°C (b) 4°C. ▲, Up term; □, Down term. (From Icier, F. and Bozkurt, H., 2009. *Food Bioprocess Technology*, 4(7), 1253–1263. With permission.)

Ohmic heating can be used to heat liquid whole egg in a fast manner. By applying a voltage gradient of 20 V/cm (Icier and Bozkurt, 2010), the liquid whole egg can be heated up to 60°C from 10°C in 105 s.

In a shelf-life study, Reznick (1996) compared conventional heating to Ohmic heating using pasteurized liquid eggs. Although the initial plate counts were similar, but as the time progressed, conventionally heated samples reached plate counts of 10,000 cfu/mL compared with Ohmically heated samples with plate counts of 10 cfu/mL after 12 weeks. This result was explained by the injury effects of the Ohmic heating to the cells due to possible electroporation.

Concentric rotational viscometer was used to estimate the change in rheological behavior of the Ohmically heated liquid whole egg, across a temperature range of 4–60°C. The Ohmic heating was conducted by applying the voltage gradient (20 V/cm) at 50 Hz. The temperature dependency of the electrical conductivity of liquid egg was linear ($R^2 = 0.999$).

The temperature sensitivity of the egg protein during thermal treatment was shown by the change in time dependency with the increasing temperature change. In continuous Ohmic heating system, flow behavior of liquid whole egg was predicted as laminar (Generalized Reynolds number range of 87.59–538.87) for the mass flow rate range of 0.0056–0.0166 kg/s. Assessment of the friction factors and pressure losses in the system was also done by Icier et al. (2010). Since there is a lack of information on the rheological changes of liquid egg during Ohmic heating in the open literature, this study gave necessary information for modeling and designing of the Ohmic heating systems for liquid egg products.

Understanding the rheological behavior of liquid egg products with a wide range of temperature has provided information of great importance for the integration of new processes to the egg product industry. In order to allow the adequate process design, operation, and control, the knowledge of the rheological behavior of whole egg as affected by temperature is of fundamental importance. Ohmic heating could cause minimal structural changes due to its ability to heat the liquid whole egg faster and uniformly, and due to additional electrical effects rather than thermal effects at different voltage gradients could affect its rheological behavior unexpectedly due to the higher amount of the denaturation of proteins and other structural breakdowns (e.g., electroporation effects). Further work is needed to investigate the possible different effects of electrical treatments on the quality, nutritional properties, the chemical structure and functional properties of the liquid egg products compared to conventional heating methods.

19.9 CURRENT STATUS AND TRENDS

Ohmic heating is applied to liquid and semi-liquid foods such as fruits and vegetable products (juices, purees, pulps, etc.), milk, ice-cream mix, egg, whey, soups, stews, heat-sensitive liquids, soymilk, and so on, for various processing methods such as heating, pasteurization, and sterilization. It could also be used for blanching, thawing, cooking, fermentation, peeling of fruits, and processing of protein-rich liquid foods for formation of protein films and gels. It is also applied as a pretreatment method for dehydration and extraction (Icier, 2003; Sastry, 2008).

Ohmic heating is an exceptional substitute to main food-processing methods, which shows some promise in the food-manufacturing business. This technology has been evolved greatly since 1990 and with time it will become more updated and competent (Anderson, 2008).

Ohmic heating has limited commercial applications throughout the world. Some of the examples with the capacities of 36 tons/h for processing are: whole fruits (Japan); liquid egg (USA); Japanese breadcrumbs (UK); tofu (Japan); low-acid meats and vegetables in bags (UK); baby food, artichokes, carrots, mushrooms, ketchup, fruit nectars, fruit juice, peppers, cauliflower, tomato paste, sausages, and fruit puree; fruit slices and large fruit pieces in syrup (Europe, Japan, Mexico, South America, etc.) (Icier, 2003; Anderson, 2008; Bozkurt and Icier, 2009; Sastry, 2009).

Customization of Ohmic heaters can be done for different foods, varying according to their electrical conductivity range. In addition, a variety of novel products can be developed by controlling their electrical conductivity changes. Ohmic heating may decrease the lag period of fermentative bacteria and could be of benefit to fermented products like beer or wine by decreasing the processing time. Research is required on methods for identification, measurement, and testing for cold-spots and overheated regions during Ohmic heating of multiphase foods. There is still a lack of understanding on the effectiveness of Ohmic heating for pathogenic bacteria inactivation.

Further studies are required for modeling, measurement, and verification of the heating of solid-liquid mixtures (Sastry, 2008). Commercialization of Ohmic heating technology is also dependent on the development of satisfactory safety and quality-assurance code of behavior in order to attain an approved filing of the process with the FDA for all possible food materials (Ye et al., 2003).

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20 Fruits and Vegetables

Gary Tucker

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20.1 INTRODUCTION

One of the real successes of Ohmic technology has been in the area of fruit and vegetable processing, and in particular fruits whereby the natural levels of acidity enable ambient stable products with long shelf lives. Fruits and fruit products only require a pasteurization treatment using temperatures below 100°C. This avoids the need to operate the processing system above atmospheric pressure and therefore simplifies operation. It also reduces damage to fruit identity caused by pressure differentials and in particular, the pressure reduction to bring the system pressure back to atmospheric.

Choice of the level of pasteurization depends on the product pH. Recommended thermal process times and temperatures given in Table 20.1 are designed to achieve a 6-log reduction in microorganisms. Fruit products pasteurized according to the times and temperatures in Table 20.1 are stable under ambient conditions, and so do not require refrigeration. These are equivalent times and temperatures and so a process at a higher temperature would require a shorter time, and vice versa.

As the product pH increases, the levels of heat resistance of microorganisms also increase, so a longer time and/or higher temperature are required to achieve the same 6-log reduction. Another factor is the increasing range of microorganisms that can tolerate the decreasing levels of acidity (with increasing pH). For example, below pH 3.7 it is only yeast, mold, and some lactic acid bacteria that can survive, and these are easy to kill off with a mild process equivalent to 5 min at 70°C. However, between pH 4.0 and 4.5 there are various bacteria that produce heat-resistant spores that can survive and spoil the products. Fortunately with low pH products, there are very few food safety microorganisms that need to be considered (*E. coli* is an exception but is not heat resistant).

20.2 RESEARCH ON FRUIT AND VEGETABLE PRODUCTS

As stated above, fruits are an ideal product for Ohmic heating because of their natural acidity that permits a lower heat treatment than with low acid foods. Also, delicate particulates such as strawberries and certain vegetables benefit from a volumetric heating technology in which the particulate can be forced to heat preferentially to the carrier liquid. The result is a variety of processed fruit and vegetable products of high quality that are unique to Ohmic heating.

TABLE 20.1
Recommended Times and Temperatures to Achieve a 6-log Pasteurization Process
for Fruit Products as a Function of pH

pH of Product	Target Microorganisms	Reference Temperature (°C)	z-Value (°C)	Recommended Time and Temperature
<3.7	Spores of yeast and mold, and <i>Lactobacilli</i>	70	7.5	5 min at 70°C
>3.8	<i>E. coli</i>	70	7.5	2 min at 70°C
3.7–4.0	Spore-forming bacteria, mainly butyric anaerobes	85	8.3	5 min at 85°C
4.0–4.2	Spore-forming bacteria, butyric anaerobes	95	8.3	5 min at 95°C
4.2–4.5	Spore-forming bacteria, butyric anaerobes	95	8.3	10 min at 95°C
>4.5	Spores of <i>Clostridium botulinum</i>	121.1	10	3 min at 121.1°C

Source: Data from Campden BRI. 2006. *Pasteurisation—A Food Industry Practical Guide*, 2nd Edition. Guideline 51, Campden BRI, Glos. GL55 6LD, UK. ISBN 978 0 905942 89 6.

There are a small number of research papers that describe Ohmic heating tests on fruits and vegetables. Access to Ohmic heating equipment for research purposes is not straightforward and this is one of the factors that has resulted in the limited research work available in the public domain.

Castro et al. (2004) investigated the effects of Ohmic heating on the electrical conductivity of a number of strawberry products. When pulps were subjected to multiple thermal treatments, their electrical conductivity decreased after the first heat treatment irrespective of the first treatment method. They also demonstrated the importance of evaluating the electrical properties of the food intended for Ohmic heating; strawberry topping and strawberry pulp showed significant differences in electrical conductivity and consequently different heating rates. Kinetic parameters of ascorbic acid degradation during both conventional and Ohmic heating were found to be identical (first-order kinetics between 60°C and 97°C), indicating that the presence of an electric field did not appear to influence the degradation of ascorbic acid.

Leizerson and Shimoni (2005) investigated the influence of Ohmic heating on the shelf life of orange juice. Their findings indicated that the sensory shelf life of orange juice could be extended to more than 100 days, doubling the expected life compared with conventional pasteurization. Pasteurized orange juice, which had been heated at 90°C for 50 s was compared with orange juice that was treated at 90°C, 120°C, and 150°C for 1.13, 0.85, and 0.68 s, respectively, in an Ohmic heating system. Retention of pectin and vitamin C was reported to be similar for the two technologies. Both thermal treatments prevented the growth of microorganisms for 105 days. However, the sensory shelf life of Ohmic heated orange juice (at >100 days) was almost two times longer than that of conventionally pasteurized juice.

The heating rate of multiphase systems will depend on the electrical conductivity of the different phases. A model system that simulated Ohmic heating of apple particulates in an isotonic carrier liquid has been investigated to determine the effect of salt addition on electric conductance and heating rate (Wang and Wu, 1999). Particulates exhibited lower electrical conductance than the tested carrier fluids at ambient temperature, but the electric conductance of the particulates increased as the temperature increased and therefore the particulates reached pasteurization temperature more rapidly. The addition of 0.05% sodium chloride or 0.31% potassium citrate to the sucrose carrier

fluid containing 1.0% citric acid increased the heating rates of both vacuum-infiltrated particulates and the fluid.

The use of Ohmic heating to increase the yield of juice from cellular tissue during apple juice production has been investigated (Wang and Sastry, 2002). The application of a current increased the juice yield from 596 to 636 ml/kg and reduced the work required to extract the juice from 0.51 to 0.36 kJ/kg, with an end temperature of 40°C observed. Vikram et al. (2005) compared the thermal degradation of nutrient in orange juice processed by Ohmic, infrared, microwave, and conventional heating. Of the four technologies, Ohmic heating gave the maximum retention of vitamin C.

The application of Ohmic heating for the sterilization of cauliflower was studied by Eliot et al. (2001) at 130°C and with a minimum holding time of approximately 20 s. The Ohmically heated cauliflower pieces ($\leq 2 \text{ cm}^3$) maintained microbial sterility during storage at 25°C and 37°C, but not at 55°C. Some preheating of the cauliflower at 50°C for 30 min or at 60°C for 20 min was carried out to help preserve cauliflower texture.

High-temperature short-time treatments of vegetables often require pretreatments, such as blanching, which is aimed at degassing, reducing volume, enzyme inactivation, and/or improving texture. It is desirable to minimize vitamin and nutrient losses occurring during the process. Sensoy and Sastry (2004) stated that Ohmic blanching of mushrooms enabled heating of mushroom in much less water (40–50% of the solid content) than used in conventional blanching (typically 400 L of water for 60 kg of mushrooms). They concluded that Ohmic blanching helped improve process efficiencies of mushroom processing.

Eliot and Goullieux (2000) stated that the blanching process often softened vegetables. However, they also referenced several studies that showed conventional blanching in the low-temperature range (50–70°C) gave a firmer texture than conventional blanching (93–100°C). Their study showed that although Ohmic heating of samples treated with low-temperature blanching did lose some firmness, a twofold increase in firmness was still found compared to conventional blanching.

Icier et al. (2006) investigated the use of Ohmic heating to achieve effective blanching of pea purée (for the baby food industry) as an alternative to the more usual water blanching. Ohmic blanching with voltage gradients in the range of 20–50 V/cm were tested against water blanching at 100°C for the efficiency of blanching. This was assessed by determination of peroxidase inactivation after blanching. At voltage gradients of 30 V/cm and above, critical peroxidase inactivation times were shorter than water blanching at 100°C. Color quality was also found to improve with voltage gradient.

Much of the advances in Ohmic heating for fruits and vegetables have taken place using commercial equipment. Information from commercial trials does not often get into the public domain and so there may be more applications than reported here. However, the suppliers of Ohmic heating equipment present brief information on products manufactured by the companies that purchased their equipment. The available information is discussed in the following section.

20.3 COMMERCIAL FRUIT PRODUCTS

The two equipment companies responsible for most of the Ohmic heating applications in Europe with fruits and vegetables are Emmepiemme (Italy) and SPX (formerly APV Ltd, UK). Section 5 in this book describes equipment for Ohmic heating and so the detail will not be repeated in this chapter. There are other vendors with a small market share, but this chapter will focus on applications with these two companies.

APV Ltd was the first UK company to sell a commercial Ohmic heating system for food processing (Skudder, 1988). One of their first 75 kW Ohmic systems has been in commercial use in the United Kingdom with fruit products for over 10 years. It started with whole strawberry products for the stir-in yogurt market and has diversified to most types of fruit together with fruit purees and jellies. These fruit products are mostly less than pH 4.0 and so the target pasteurization treatment

TABLE 20.2

Industrially Processed Products in Emmepiemme Equipment Based on 2002 Data (Plant Capacities from 1000 to 6000 kg/h)

Product (Packaged in Aseptic Bags)	Process Temperature (°C)	ΔT (°C)	Heater Power (kW)
Tomato ready-to-serve sauces ^a	110	50	50
Mango puree	105	20	64
Tomato paste	100	30	64
Diced tomatoes	105	70	70
Tomato puree	120	50	70
Peaches-apricots (dices, slices, halves)	95	50	150–200
		30	100
Diced sweet peppers—zucchini	115	55	
Carrot slices	135	70	100, 130
Low-acid vegetable purees	95	30	150
Strawberries (whole, diced)	92	70	30

^a Packaged in glass jars.

is equivalent to 5 min at 85°C. This needs to be achieved in a holding tube that connects the Ohmic column exit to the cooling tubes or hot filling equipment.

The APV system consists of a vertical up flow heating tube in which the electrodes provide the energy to increase the product temperature. The holding tubes that connect the heater to the tubular coolers are short (10–20 m) because of the relatively high temperatures achieved at the heater outlet when compared with the target pasteurization treatment of 5 min at 85°C.

The Italian company Emmepiemme has a number of Ohmic applications for fruit and vegetable products. Table 20.2 summarizes these processes. Equipment differs from the APV system in that the electrical heating tubes are usually orientated horizontally.

One of the challenges with a continuous heating system is selecting the most appropriate validation technique. Section 9 details validation methods for all food products and so information provided in this chapter is specific to work carried out by the author. Confirmation of the process for fruit and vegetable products requires a technique that can measure at the center of a particulate. Options are limited to encapsulating either a microbiological or biochemical time–temperature integrator (TTI) within some form of simulated particulate. Many of the processes for the fruit products processed in this 75 kW APV system were validated using the biochemical TTI method of Tucker et al. (2002). One of the challenges with a fruit product is to ensure the center of the largest (and slowest moving) piece of fruit receives sufficient pasteurization. This method is described in more detail in the following section on validation.

20.4 THERMAL PROCESS VALIDATION

One of the main concerns over Ohmic heating is how to ensure that the desired scheduled process has been delivered. As with other thermal processes, the scheduled process needs to be validated. Since Ohmic heating is fundamentally a thermal process, temperature and time are the principal critical process factors. With fruits and vegetables, it is usually the process at the center of the slowest heating particulate that is required. This dictates that miniature devices are embedded into the particulates so they experience the process at the particulate centers. The measured log reductions can be converted back into *F*-values using established kinetic data. Note that the generic term *F*-value will be used to refer to a process value with no specific reference temperature or *z*-value.

The theory behind microbiological reductions by heat is that the kinetics of the target microorganism is approximately first order. Thus, an F -value calculated using log reductions would be the same as that calculated from the time–temperature integration (see Equation 20.1).

$$F = \int_0^t 10^{\frac{T-T_{\text{ref}}}{z}} \cdot dt = D_T \cdot \log\left(\frac{N_0}{N}\right) \quad (20.1)$$

where

T is the product temperature, °C

T_{ref} is the reference temperature for the D_T value, °C

t is the process time, min

z , the kinetic factor, is the temperature change required to effect a 10-fold change of the D_T value, °C

There are two main measurement techniques that are classified as log reduction methods, and these use:

- Microorganisms of known heat resistance, usually in spore form, in which the initial number (pre-process) and final number (post-process) are counted and used to calculate an F -value
- Biochemical systems, in which the initial concentration (pre-process) and final concentration (post-process) are measured and used to calculate an F -value

Figure 20.1 shows a photograph of both types of measurement techniques. The alginate spore beads can be prepared using a high proportion of food material, typically >90%, which ensures the beads behave in a similar manner to the food. The silicone tubes used for enclosing the biochemical solutions are chosen so the density and thermal properties also match closely those of the food.

Irrespective of which technique is used, it is critical that the z -value is close to that for the target microbial species, preferably within 2–3°C. If the z -value is not close, the processing temperature should be close to the reference temperature, otherwise significant errors can arise between values estimated using log reduction and probes (from Equation 20.1). Also, the decimal reduction time should allow sufficient log reductions to be measured so the process can be calculated. A test that results in no surviving spores or no biochemical activity, does not allow the process F -value to be calculated, and raises doubt as to where or when the total kill occurred. Some further detail is now given of each method.

20.4.1 MICROBIOLOGICAL SPORE METHODS

These are sometimes referred to as direct methods, but they in fact rely on measuring the achieved log reductions for a process using a nonpathogenic microorganism and converting this into a process value for the target pathogen using Equation 20.1. No factory tests use the target pathogenic microorganisms because of (a) the hazards associated with their handling in a factory environment and (b) there would not be any organisms that survive the process.

A microbiological method can be conducted using organisms distributed evenly throughout a food product (inoculation) or encapsulated in gel (alginate beads). The organisms are usually in their spore form because of the greater flexibility this provides in their use.

An inoculation test measures the average thermal process within the food material inoculated. If the product is liquid it is relatively easy to introduce the spores, but for particulates it is necessary to first mix the spores into one of the ingredients to ensure that they are dispersed evenly throughout



FIGURE 20.1 Picture of alginate spore beads and amylase TTI tubes.

the particulate. Dispersion of the inoculum into the food dilutes the initial number of spores, usually to 10^3 – 10^5 /L, which reduces the F -value range that can be measured.

WORKED EXAMPLE

The following example for an inoculation test uses 10 g of spores of *Clostridium butyricum* supplied by a microbiology laboratory with a measured $D_{93.3}$ value of 1.2 min and at a concentration of 5×10^7 /g. A 1000 L batch of liquid food is inoculated with these microorganisms. The question is “What is the maximum process value that can be measured with these spores?”

Equation 20.1 is used in the calculation:

$$F = D_T \cdot \log\left(\frac{N_0}{N}\right)$$

It is assumed that the food density is 1000 kg m^{-3} , which is equivalent to 1 g cm^{-3} .

The initial numbers of spores in the 1000 L batch (N_0) is diluted to $10 \times 5 \times 10^7/1,000,000$ or 500 spores/cm³.

If we assume that the limit for spore numbers at the end of the process (N) is unity (1), then the equation becomes:

$$F = 1.2 \log \left(\frac{500}{1} \right) = 3.3$$

Hence, the maximum F -value that can be measured with these spores is 3.3 min equivalent at 93.3°C.

An encapsulation test allows the organisms to be placed at precise locations within a food particulate, by encapsulating spores in an alginate bead. The beads can be made with a high percentage of the food material so the heating rate is similar to the food (Gaze and Brown, 1990). The number of spores per bead is usually greater than for an inoculation test and can be of the order of 10^{6-8} per bead.

WORKED EXAMPLE

The following example for an encapsulation test also uses spores of *Cl. butyricum* with a measured $D_{121.1}$ value of 1.2 min and at a concentration of 5×10^7 /g. The alginate bead weighs 0.2 g and is inserted at the center of a 10 mm cube of carrot. The question is the same, which is “What is the maximum process value that can be measured with these spores?”

The initial numbers of spores in each bead (N_0) is $0.2 \times 5 \times 10^7$ or 1×10^7 spores in the bead.

The same limit for spore numbers at the end of the process (N) applies (1), then the equation becomes:

$$F = 1.2 \log \left(\frac{10,000,000}{1} \right) = 8.4$$

Hence, the maximum F -value that can be measured with these spores is 8.4 min.

20.4.2 BIOCHEMICAL SYSTEMS

These can be enzymes, such as amylase or peroxidase, which denature (an unwinding of the structure) during heating with similar kinetics to that of the target microbial species. Most enzyme systems are limited to pasteurization because the enzymes secreted by microorganisms are designed to operate at moderate temperatures. One exception is work by Tucker et al. (2007) in which amylase from the hyperthermophilic organism *Pyrococcus furiosus* is being used. This organism grows in saltwater pools in volcanic regions, such as Vulcano Island in Italy, and the amylase it secretes is genetically designed to be thermostable.

Calculation of F -values uses the initial and final enzyme activities as in Equation 20.2, which also assumes the first-order thermal death time model applies. This is the same equation for calculating integrated process values when using microbiological spore methods except that the number of organisms is replaced by the amylase activity.

$$P = D_T \cdot \log \left(\frac{A_{\text{initial}}}{A_{\text{final}}} \right) \quad (20.2)$$

where

A_{final} is the final activity after a specific time–temperature history, s^{-1}

A_{initial} is the initial activity, s^{-1}

D_T is the decimal reduction time to achieve a 1-log reduction in amylase activity, s

TABLE 20.3**Key Attributes of the *Bacillus amyloliquefaciens* α -Amylase TTI**

Category	Description
Operating principle	Reduction in amylase activity in response to time and temperature
Measurement method	Amylase assay to measure absorbance rate, using a spectrophotometer
Active temperature range	60–100°C
Kinetic factor, or z -value	$9.7 \pm 0.3^\circ\text{C}$
Decimal reduction time	$D_{80.7} = 18.7$ min
Process value	Pasteurization value
Sample size	0.02 mL

Biochemical systems are often referred to as time–temperature integrators (TTIs) although strictly speaking the term TTI is also applicable to microbiological systems. Encapsulating the TTI is an essential step that prevents it coming into contact with the food or processing environment. The amylase solution is recovered from the tube using a hypodermic syringe.

Amylase solutions are one of the few biochemical systems with appropriate kinetics (Tucker, 2000), which requires (a) the D -value to be large enough for residual activity to remain after the process and (b) the z -value to be close to 8–11°C typically measured for microorganism death. Table 20.3 illustrates some of the key attributes of a specific amylase TTI system that is suitable for measuring processes with high-acid fruits.

Tucker et al. (2002) validated the use of an industrial Ohmic heat exchanger (75 kW, APV Ltd.) to process fruit pieces (up to 12 mm cube) with biochemical time temperature integrators (TTI). An α -amylase from *Bacillus amyloliquefaciens* and another from *Bacillus licheniformis* were used. Amylase activity before and after processing was correlated to the inactivation of a target microorganism. Despite operating to represent “worst case” conditions, pasteurization values from this study showed a substantial safety margin on the target process of 85°C for 5 min.

20.5 CONCLUSION

It has been shown with fruit and vegetable products that Ohmic heating can provide an effective alternative to a conventional heat exchanger for thermal processing applications. The rapid volumetric heating nature of Ohmic enables fruit and vegetable identity to remain excellent during heating. Any damage to particulate identity tends to occur during cooling, which uses conventional tubular heat exchangers, as a result of shear damage against the exchanger walls. By removing the need to cool fruit products, and filling hot into a package such as a glass jar or plastic pack, there is significant potential to minimize particulate damage. This area of hot filling is one that deserves greater attention.

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21 Commercially Successful Applications

Gary Tucker

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21.1 INTRODUCTION

Commercial Ohmic heating systems are available from a number of suppliers including SPX (formerly APV, Crawley, UK), Raztek Corp. (Sunnyvale, CA, USA), Emmpiemme SRL (Piacenza, Italy), and Simaco (Piacenza, Italy). A number of companies are rumored to be investigating this technology, and it is estimated that there are at least 18 commercial plants in operation across Europe, the United States, and Japan (Ruan et al., 2004). In addition, Emmpiemme SRL equipment has been supplied to Mexico and the Ivory Coast for strawberry processing and tomato and mango processing, respectively (G. Tucker, personal communication). Products such as liquid egg and low-acid ready meals are also being produced (Giese, 1996). The uniform and rapid temperature increase that occurs with Ohmic heating can reduce “over cooking” of these products compared to that with conventional heat exchangers. Ohmic devices have also been investigated for other applications such as extraction or blanching in the food industry, these are also discussed later in the chapter.

However, the real success of this technology has been in the area of fruit and vegetable processing, and multiphase products. Fruit and vegetables are considered in detail in Chapter 20 and so only an overview will be given in this chapter. Some examples of products and industrial plants installed by Emmpiemme SRL is given in Table 21.1.

APV produce two commercial systems with power outputs of 75 and 300 kW, corresponding to product capacities of 750 and 3000 kg/h, respectively, for a temperature rise of 75°C in water. Emmepiemme produces systems in the range of 60–480 kW, for production throughputs of 1000–6500 kg/h. Systems can be based on the in-line design or coaxial (cross-field) design; in the former case the electrodes protrude into the product, whereas in the latter the flow passes through a column surrounded by an electric field.

Ohmic heaters can be used for the production of ambient stable products, with filling options that include ultra-clean (dependent on product type), aseptic or hot fill technology. This ensures that recontamination of the product after the thermal process is controlled, either by the filler hygiene or

TABLE 21.1**Examples of Industrially Processed Products in Emmepiemme Equipment**

Product	Process Temperature (°C)	ΔT (°C)	Heater Power (kW)
Tomato ready-to-serve sauces ^a	110	50	50
Mango puree	105	20	64
Tomato paste	100	30	64
Diced tomatoes	105	70	70
Tomato puree	120	50	70
Peaches-apricots (dices, slices, halves)	95	50	150–200
		30	100
Diced sweet peppers—zucchini	115	55	
Carrot slices	135	70	100, 130
Low-acid vegetable purees	95	30	150
Strawberries (whole, diced)	92	70	30

Source: Data from Margas, E. 2012. Emerging technologies for new products. Scottish FHIS. http://www.foodhealthinnovation.com/media/1293/new_technologies_for_product_innovation.pdf.

Note: Plant capacities from 1000 to 6000 kg/h. Products packaged in aseptic bags apart from ^apackaged in glass jars.

by the lethal heat from a high filling temperature. Ohmic heating technology is therefore a compatible technology for use in aseptic processing systems, which is an area that has seen considerable growth in recent years. Use of the aseptic fill can allow preservatives to be removed from the product where appropriate.

21.2 OHMIC: A THERMAL PROCESS ALTERNATIVE

Research has been carried out on the Ohmic treatment of a wide range of products. This has meant that a substantial body of data has been compiled relating to suitable operational parameters for numerous product categories. A selection of these papers is included below to illustrate the range of applications.

Irudayaraj (2000) investigated the effect of Ohmic heating on the quality of UHT milk. Temperatures of 135°C, 145°C, and 155°C and holding times of 0.5 and 4.0 s were investigated. Volatile flavor compounds were identified using GC mass spectrometry and sensory evaluations were carried out. It was reported that cooked, sour, and stale flavors in the Ohmically heated samples were much lower than the commercial variety. In addition, protein denaturation in Ohmic heated milk was less than half of the commercial variety tested.

Reconstituted skimmed milk powder was heated to 68–75°C (similar to pasteurization temperatures) to observe whether fouling occurred as in conventional processes (Bansal and Chen, 2006). It was found that the electrodes became fouled during the heating process, especially at high protein concentrations.

A number of liquid egg producing facilities now use Ohmic heating to deliver the pasteurization process. Raztek's Electroheating™ technology has been implemented in an industrial site at flow rates over 11,300 kg/h (<http://www.raztek.com/testimonials.html>). Significant increases in the shelf-life of the product are reported for the Ohmically heated process compared to the conventional process. The increase in shelf-life has greatly reduced the amount of returned products. In addition, Raztek claims that Ohmic heating does not cause fouling arising from a coagulated product, allowing the process to be effectively operated without interruptions for cleaning. Additional savings can therefore be made through reduced cleaning costs and down time.

Miao et al. (2002) carried out tests on the rheological properties of egg (0–2% salt) under different conditions of Ohmic heating and found that the viscosity decreased while the elasticity increased with an increasing salt content in the range of 0–0.5%. There was an apparent affect of applied voltage (19–73 V at 63 Hz) on the viscoelasticity of the coagulated egg.

Castro et al. (2004) investigated the effects of Ohmic heating on the electrical conductivity of a number of strawberry products and the application of Ohmic heating for the sterilization of cauliflower was studied by Eliot-Godereaux et al. (2001). Details of these two papers are given in Chapter 20.

Application of Ohmic heating to solid foods, not held within a liquid, has proven problematic because good contact is required between the electrode plates and the product. Hamburgers are a notable exception because they are flat and can be placed between two plates. Özkan et al. (2004) showed that the cooking time of a hamburger in grill plates could be reduced from 163 to 117 s by the application of 50 V AC. Ohmic heating has also been applied to meat emulsions such as those used in sausages (Piette et al., 2004; Shirsat et al., 2004). These reports suggest that cooking time can be significantly reduced with insignificant effect on consumer acceptability.

Oregon State University has been very active regarding research into Ohmic heating of fish products, with a number of reports since 1992 that are listed on their website (<http://osuseafoodlab.oregonstate.edu/seafoodlab/publications.htm>). For example, Wu et al. (1998) developed a multi-frequency Ohmic heating system with a 30 Hz to 1 MHz range for measuring electrical conductivity and absolute dielectric loss of food samples. Surimi paste and stabilized mince from Pacific whiting (hake), in the 20–70°C range were tested at frequencies from 55 Hz to 200 kHz. DC electrical conductivity and absolute dielectric loss of Pacific whiting surimi paste increased with temperature and salt concentration. Both factors also increased with temperature for the stabilized mince.

21.3 PRODUCT DEVELOPMENT CONSIDERATIONS

A pre-process assessment of the product should be carried out to determine the heating behavior of the product (Zoltai and Swearingen, 1996). This includes considering factors such as product conductivity, carrier fluid viscosity, product stability, and particle characteristics (shape, size, concentration, and density). Zoltai and Swearingen (1996) also reported that, for particle concentrations between 20% and 70%, the lower concentrations generally required a carrier fluid of higher viscosity. In addition, if gelatinization of starch in the carrier fluid takes place it can lead to uneven heating; they therefore recommend pre-gelatinization in these cases. Specific heat capacity (SHC) must also be taken into consideration, as if two components of the product have the same conductivity but different SHC, then their temperature rise will be different.

Pilot scale equipment is available in Italy and France through Emmpiemme SRL, C-Tech Innovation (Capenhurst, UK) and a number of academic institutions in the US. Evaluation of the product characteristics that lead to uniform heating is essential, as is an evaluation of product quality attributes that may change during processing. It is true to state that Ohmic heating provides an almost instantaneous rise in temperature, which enables a food product to be pasteurized or sterilized within a few seconds. Thus, the food is rendered commercially sterile from a microbiological standpoint, but may not be properly cooked. This effect is critical for foods such as meat pie fillings that require texturization during the processing operation.

21.4 CONTROL

Sophisticated controls are required to ensure the correct thermal process is delivered, and in particular to ensure that run-away heating does not occur. Run-away heating is associated with the change in electrical conductivity of the product, which allows it to draw more heat as its temperature increases. In operation, constant changes to the parameters may be required to allow for changes

in the SHC or product conductivity. The Raztek Corporation state that the temperature of their Electroheating™ systems is controlled by the voltage and they have computerized controls allowing the temperature to fluctuate only 1°C from the set point. Raztek claims that the system is relatively insensitive to sharp changes in flow rate that otherwise can cause over heating of the product. User-friendly process control is an essential requirement for Ohmic heating as anecdotal evidence would suggest the food companies that evaluated the technology in the 1980s discovered that results were excellent when the units were operated by highly trained technicians, but variable when the units were operated by unskilled factory operatives.

21.5 THERMAL PROCESS VALIDATION

One of the main concerns over Ohmic heating is how to ensure that the desired scheduled process has been delivered. As with other thermal processes the scheduled process needs to be validated. Extensive measurement of the product thermal properties, evaluation of the coldest point along the tube and residence time distribution (RTD) tests should be made.

Since Ohmic heating is fundamentally a thermal process, temperature and time are the principal critical process factors. However, Ohmic heating generates internal energy during the process; therefore no theoretically upper temperature limit to the process can be given. Blockages or other hold-ups could lead to boiling within the system. While hot spots are a product quality problem, locating possible cold spots is a food safety issue that must be resolved so that time–temperature measurements can be made in these spots. Ruan et al. (2004) reviewed a number of models for predicting the Ohmic heating behavior and also the use of magnetic resonance imaging (MRI) to determine the cold spot in the tube. They conclude that the long data-acquisition time makes the technique unsuitable for the dynamic process.

With a continuous flow Ohmic heater, there are several other factors that influence the temperature. These include the electrical conductivity of the different phases, the temperature dependence of the electrical conductivity, the heating device design, the fluid motion, RTD (sometimes referred to as passage time distribution, PTD), the thermophysical properties of the food, and electric field strength (US FDA, 2000).

There are two factors that can aid in the ease of validating Ohmic heating on low acid products; these are (1) the possibility of faster heating of the particulates having lower electrical conductivity than the fluid, and (2) a near plug flow behavior of products with high solid content (Kim et al., 1996). These allow the microbiological safety of these types of products to be ensured based on the measurement fluid temperature and the conservative laminar flow residence time limit. However, this is not the case where the particles heat slower than the liquid. Local variations in temperature due to nonuniform conductivity must also be considered.

Historically, there have been a number of investigations into the temperature distribution within the Ohmic heater and the conductivities of food substances (US FDA, 2000). Significant research has gone into determining the worst-case scenario (Zhang and Fryer, 1993; Sastry and Salengke, 1998), as unlike conventional heating, the worst case may not be associated with a static situation.

RTD of a starch solution and carrot particles/starch solution, in continuous Ohmic heating has been investigated using ultrasound (Marcotte et al., 2000). Ultrasonic sensors were placed at the end of the tube to measure changes in sound attenuation. For liquid experiments, a copper pigment was used, as the ultrasound tracer and copper concentration was determined in samples at timed intervals. Results of both analysis types compared well.

Tucker et al. (2002) validated the use of an industrial Ohmic heat exchanger (75 kW, APV Ltd.) to process fruit pieces (up to 12 mm cube) with biochemical time–temperature integrators (TTI). α -Amylase from *Bacillus amyloliquefaciens* and another from *B. licheniformis* were used. Amylase activity before and after processing was correlated to the inactivation of a target microorganism. Despite operating to represent ‘worst case’ conditions, pasteurization values from this study showed a substantial safety margin on the target process of 85°C for 5 min.

Hall-effect sensors have also been used to investigate the movement of particles through an Ohmic heater (Kim et al., 1996; Eliot-Godereaux et al., 2001). Tucker and Withers (1994) first showed that the Hall effect could be used to measure the passage of a magnetic field through stainless-steel pipes of a food processing system. This was used on a commercial Ohmic heater by Tucker et al. (2002) in which various particulate fruit products were processed. Eliot-Godereaux et al. (2001) determined the PTD of sodium alginate particles through a 10 kW APV Ohmic heater. At least 50 particles were used per run to obtain a representative sample of the PTD. Mean normalized passage times decreased with increasing flow rate and the same was observed for the minimum and maximum normalized passage time. The mean normalized passage time remained constant with increasing solid concentration.

Gaze and Brown (1990) used alginate particles with immobilized microorganisms to assess the lethality of UHT processes. For a continuous Ohmic process the heating regime was found to be equivalent to 32 min at 121.1°C using thermocouples, assuming heterogeneous flow. Lethality values equivalent between 24 and 31 min at 121.1°C were found when using *B. stearothermophilus* spores immobilized in meat/alginate and between 28 and 39 min at 121.1°C for carrot/alginate particles. In the case of spores isolated at the center of meat/alginate particles, process lethality values equivalent between 38 and 37.5 min at 121.1°C were obtained.

Palazoglu et al. (2003) investigated the thermal profile of a heat exchanger using magnetic switch implants with predetermined temperatures of magnetic signal change (125°C and 138°C). First they were checked using a bench-top magnetic field testing installation. Magneto-resistive sensors were arranged linearly along heating and holding sections of a heat exchanger; this system provided a total of 256 sensing locations along the monitored length of process equipment. Results showed a feasibility of implementing a conservative process monitoring and validation methodology for continuous thermal aseptic processing of products containing particulates, it is possible that this could also be applied to Ohmic heater validation.

21.6 OPERATIONAL COSTS

In the early 1990s an economic analysis, conducted at the University of Minnesota (USA), indicated that Ohmic heating would be economically viable for premium quality foods. However, the cost of Ohmic systems has decreased greatly since that time, and the range of products for which Ohmic heating may be economically feasible has expanded considerably. Ohmic heating costs were found to be comparable to those of typical retort processes of high-acid foods (Allen et al., 1996). However, for low-acid foods, Ohmic heating is not the low-cost option, but quality advantages must be recognized.

A case study based on pasteurization of fruit juices suggested that electricity costs equated to 0.245% of the total product cost. This was based on an electricity cost of 7 cents per kWh (i.e., 3.5p/kWh), therefore comparable with the UK approximate cost of 4p/kWh and a product cost of \$1000 (ca. £500) per ton. In this case study, the product entered the Ohmic column at 5°C and exited at 95°C. A rapid vacuum cooler regenerated 66% of the heat, about 60°C and the ElectroheaterTM added 30°C. This equated to 30,000 kcal per ton or 35 kWh; all of the power was assumed to turn into heat as the process is very efficient. The heater did not become fouled, which allowed cleaning operation to be minimized, in this case for weeks without cleaning, which greatly reduced cleaning costs and down time.

21.7 NONPRESERVATION APPLICATIONS FOR FOOD

Ohmic heating has shown its potential as an alternative to conventional thermal processes, as discussed above. There is also hope for the use of Ohmic devices where heating the product for microbial destruction is not the aim, for example, to aid in yield production or extraction, evaporation, and thawing. These applications are discussed below.

Cho et al. (1996) developed a hydraulic press with Ohmic heating equipment for dewatering of soybean milk residues. The moisture content of residue from the conventional hydraulic press was 74%, but could be reduced to less than 70% using the Ohmic heating press. Dewatering was maximized by the application of an alternating current of 5 Hz at 60 V.

Rice bran is a by-product of the rice milling process. Millions of tons per year are wasted due to rancidity. Extraction of bio based components, such as rice bran oil can be useful because they can be used in the production of nutraceuticals, as specialty chemicals or in fuels. Ohmic heating has been demonstrated to be effective in increasing the yield of lipid from rice bran from 53% to 92% (Lakkakula et al., 2004). In the same study it was found that lowering the frequency could increase the yield.

Vacuum evaporation is one of the most popular processing methods for juice concentration. Problems with product quality associated with vacuum evaporation include aroma loss, flavor reduction and color change. The process is also time-consuming because increasing viscosity results in poor heat transfer. Trials conducted by Wang and Chu (2003) showed that in a 40 min process, vacuum evaporation by Ohmic heating could evaporate moisture three times more effectively than traditional processes, and viscosity increase was no longer a significant issue.

In 1990, de Alwis and Fryer investigated electroconductive thawing. Ohmic technology has since been proposed as a fast and economic means for thawing frozen fish. Water immersion thawing has a number of disadvantages including: long thawing times, potential for cross-contamination, prolonged exposure of the outer regions to warm temperatures, the use of large amounts of water, and the generation of large amounts of wastewater. Professor Murat Balaban, of the Institute of Food and Agriculture Science, University of Florida, has presented a number of papers on the use of Ohmic devices to thaw frozen fish products.

Ohmic thawing has been demonstrated to thaw blocks of shrimp in comparable times to conventional thawing (Roberts et al., 2002), proper control of the operation was reported to eliminate local overheating. Ohmic thawing was also reported to be economically advantageous. This study compared sensory, microbial, and quality attributes of Ohmically and conventionally thawed shrimp. The moisture content of the shrimp after heating depended on the size of the shrimp; the moisture content of large shrimp was not significantly different than conventionally thawed samples. However, small shrimp had higher moisture content when conventionally thawed. Sensory tests and total aerobic microbial plate counts were not significantly different between conventionally and Ohmically thawed shrimp.

21.8 NONFOOD APPLICATIONS

Electrical conductivity measurements and heating trials have been performed on representative samples of dewatered sewage sludge to assess the feasibility of heating sewage sludge Ohmically to the temperatures required for pasteurization or sterilization (Murphy et al., 1991). Sewage sludge was Ohmically heated from room temperature to boiling point rapidly, uniformly, and at greater than 98% energy efficiency. The Ohmic heating process was stated to be ideally suited to the thermal pasteurization or sterilization of sewage sludge.

21.9 CONCLUSIONS

Ohmic heating devices can be used in the food industry to deliver a thermal process (pasteurization or sterilization) or to enhance other processes such as extraction. It has been shown that Ohmic heaters can provide an interesting alternative to heat exchanger for thermal processing applications. Key potential advantages of Ohmic heating over heat exchangers can be summarized as:

- Rapid uniform heating.
- High-quality products, without overcooking, in particular for particulate products where less degradation of texture, flavor and color can be seen due to the reduced time-temperature profile.

- High percentage of intact particulates due to reduced shear.
- Reduced fouling therefore longer run times on certain products, for example fruit juices and egg.
- Greater energy efficiency.

Potential disadvantages can be summarized as:

- Limited to product with ionic content (i.e., not suitable for oils, etc.).
- Very high level of control required either through specialist trained operators or complex control systems.
- Fluctuations in the flow of the product or high levels of air can lead to electrode burnout, causing production to stop and replacement of electrodes.
- Electrodes may need replacing on a regular basis (e.g., every six months).
- Lack of industry support at present due to the small number of plants in operation.
- Dairy products are still susceptible to high levels of fouling.
- Validation can be complex if particulates heat is slower than the liquid.
- Variation in heating rates of multiphase products, based on the electrical conductivity of each phase, can be advantageous or disadvantageous.

Ohmic heating can be used for the manufacture of products containing particulates which would otherwise be overcooked during the delivery of the required scheduled process in a continuous heater, and for high-quality products that do not have a cooked flavor. Validation of the thermal process through Ohmic heating, to ensure product safety, can be carried out with a number of methods as discussed above.

Significant developments have taken place in both electrode and software technology, as noted by patents and the publications above. In particular, the software is critical to the operation of the system to ensure that the process is controlled and overheating does not occur, for example, due to changes in product characteristics or flow rate.

Research has also been carried out on a number of different food types or varied conductivity. It is important to fully understand the properties of the product and how they change with temperature. Manipulation of the product's ionic content may be required in order to control the heating behavior.

In conclusion, Ohmic heating can offer a highly favorable alternative to conventional processing. It can provide high quality and/or unique products. The operation is relatively energy efficient, however, the economic justification will be on a case-by-case basis.

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Section 8

Other Applications and Future Uses of Ohmic Heating

22 Ohmic Blanching

Filiz İçier and Hayriye Bozkurt

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22.1 INTRODUCTION

Blanching is an essential prior step in vegetable processing, which destroys the enzymes and micro-organisms and helps in prevention of quality deterioration particularly during drying, freezing, frying, or storage. Besides, it also expels the air entrapped intercellularly inside the tissues. Blanching has also proved to aid reconstitution and textural improvement in the product. Hot water blanching is by far the most popular and commercially adopted process, as it is a simple technique whereby the mechanism of heat penetration is by conduction. In such systems the resistance to heat transfer at the surface is negligible compared to the internal resistance to heat transfer. It was shown that in such systems the rate of heat penetration is proportional to the square of the characteristic dimension of the object. The time required for blanching depends upon the time required for inactivation of enzymes and thus on the rate of heat transfer. The longer time required for the temperature rise at the slowest heating point, normally the geometric center of a relatively large object, could damage the quality of the kernels and result in considerable loss of nutrients such as carbohydrates, proteins, water-soluble minerals, vitamins, and sugars. On the contrary, shortening the blanching time could reduce the degree of enzyme inactivation and result in a shorter shelf life. Because of this, the practical blanching time of such product is quite often a compromise.

In recent years, alternative technologies have been gaining importance both from industry and consumer aspects all over the world. By encountering the inefficient energy usage in the industry,

some dangers that would affect our future, such as inadequate energy sources and environmental troubles, would be overcome. This also would result in providing additional economic input for that country. Electrical treatments played an important role as alternative minimal processing methods in food technology. Recently, studies showed the usage of the Ohmic heating process as an alternative blanching method for vegetables (Mizrahi et al., 1975; Mizrahi, 1996; Sensoy and Sastry, 2004; Icier et al., 2006; Allali et al., 2010). Mizrahi (1996) reported that blanching by Ohmic heating considerably reduced the extent of solid leaching as compared to a hot water process. The blanching time was short regardless of the shape and size of the product. Ohmic heating yields better products, clearly superior in quality than those processed by conventional heating. This is mainly due to its ability to heat materials rapidly and uniformly, leading to a less aggressive thermal treatment. Ohmic heating appears to be an effective method for enhancement of processes controlled by mass transfer, since it affects the integrity of biological tissue by solubilizing the pectic substances constituting the cellular wall and by providing electroporation of cell membranes (Lebovka et al., 2004a,b; Praporscic et al., 2006).

The available information about the Ohmic blanching systems demonstrated that the system is similar to other Ohmic processing systems. It consists of a power supply, an isolating transformer, a variable transformer, a microprocessor board, and the blanching cell.

This chapter introduces the basic principle of this alternative blanching technique including how it is applied and how it differs from conventional blanching. Recent literature on Ohmic blanching applications is examined, highlighting the impact of this technology on general quality aspects of foods. The system considerations, its effect on product quality, and future research needs are discussed in this chapter as well.

22.2 THE EFFECTS OF OHMIC BLANCHING

Ohmic blanching is known as an alternative blanching method due to providing rapid and homogeneous temperature distribution within the sample. The recent studies on this subject—factors evaluated and parameters applied—are presented in Table 22.1

With regard to consumer acceptance, good-quality control of fruit and vegetables is important. In this context, it is important to evaluate the impact of blanching on quality-related parameters. Food quality covers a wide range of parameters, including enzyme content, structural properties, nutritional properties, sensorial characteristics, and so on. This section gives an overview of the effect of blanching, which is a common pre-processing step in food technology, and on quality-related parameters in fruits and vegetables, within the insight of current research.

22.2.1 TREATMENT TIME AND ENERGY EFFICIENCY

Treatment time is the most important system parameter for the design of Ohmic systems. In an equal conductivity system, the energy dissipated (E) term per unit volume of the product is given by Equation 22.1 (Mizrahi et al., 1975);

$$E = \left(\frac{\Delta V}{L} \right)^2 s t \quad (22.1)$$

where ΔV is voltage difference between the electrodes, L is the distance between electrodes, t is the time, and σ is specific electrical conductivity determined by

$$s = \frac{I}{\Delta V} \frac{L}{A_e} (S/m) \quad (22.2)$$

TABLE 22.1
Studies on the Application of Ohmic Blanching

Sample	Method	Parameters	Factors Evaluated	References
Corn cob	Ohmic blanching	50 Hz 380 V/7 cm AC $T_i = 20^\circ\text{C}$, $T_f = 100^\circ\text{C}$	-Treatment time -POD activity -Electrical energy efficiency	Mizrahi et al. (1975)
Beet (whole, diced, and sliced)	Ohmic blanching	50 Hz, AC 380 V for 7 cm	-Solute loss	Mizrahi (1996)
Mushroom	Ohmic blanching	200 and 212 V for 7.3 cm 1, 10, and 100 Hz, $T_i = 25^\circ\text{C}$, $T_f = 70^\circ\text{C}$ Sinusoidal, square and triangular waves	-Temperature history -Electrical conductivity -Weight loss -Volume loss -Effect of frequency on -Effect of wave form	Sensoy and Sastry (2004)
Pea puree	Water blanching Ohmic blanching	100°C 20–50 V/cm 50 Hz $T_i = 30^\circ\text{C}$, $T_f = 100^\circ\text{C}$	-Treatment time -POD activity -Color	Icier et al. (2006)
Chowmein	Ohmic blanching	$T_i = 25^\circ\text{C}$, $T_f = 140^\circ\text{C}$ 15–20 V/cm, 60 Hz	-Electrical conductivity	Kulshrestha and Sastry (2006)
Strawberry	Ohmic blanching	230 V, 18 A, 50 Hz $T_f = 60^\circ\text{C}$ and 85°C	-Mass transfer	Allali et al. (2010)
Artichoke	Ohmic blanching	25–40 V/cm $T_f = 85^\circ\text{C}$ 50 Hz, AC	-Treatment time -Phenolic content -Vitamin C	Icier (2010)
Carrot pieces	Water blanching Ohmic blanching	85°C and 100°C 150 V, 50 Hz, AC $T_i = 4^\circ\text{C}$, $T_f = 60^\circ\text{C}$ and 90°C	-POD activity -Texture -Light microscopy	Lemmens et al. (2009)

When the product with an initial uniform temperature T_i is heated Ohmically, the time t_c (come up time) required to reach the blanching temperature, T_B , can be simply calculated by

$$t_c = \mathbf{r} \frac{C_p (T_B - T_i)}{(\Delta V/L)^2 \mathbf{s}} \quad (22.3)$$

where C_p and ρ are the specific heat and density of the product, respectively. The Ohmic heating is uniform throughout the product, whereas the heat transfer in the conventional blanching method is due to the temperature gradient between the medium and the product. Therefore, the temperature response at the center of a large solid product can be much faster in Ohmic blanching as compared to that of conduction-type heating. This behavior results in shorter required blanching time, which

was approved by several researchers. Mizrahi (1996) has reported that 2 min blanching time by Ohmic heating of whole large vegetables had similar effects with 4 min water blanching. They discussed that leaching of solutes during blanching had also followed the same pattern regardless of the heating method, and the energy dissipated by the electric current passing through the samples was capable of heating it uniformly and very fast, regardless of its shape or size.

The other important consideration for the Ohmic system is the usage of energy within the system, efficiently. The energy efficiency of Ohmic blanching system is the ratio of the energy input to the product to raise its temperature from its initial temperature, T_i , to its blanching temperature, T_B , to the total energy input to the system (Mizrahi et al., 1975):

$$h = \frac{G \rho C_p (T_B - T_i)}{((V/L)^2 \rho (V_s + G t_R))} \quad (22.4)$$

where η is the energy efficiency, G is the volumetric flow rate of the product through the system, t_R is the residence time of the product in the system and V_s is the volume of immersion solution. Combining Equations 22.3 and 22.4 yields:

$$h = \frac{G t_c}{(V_s + G t_c)} \quad (22.5)$$

The maximum electrical energy efficiency that can be obtained in the Ohmic blanching cell is determined by the ratio of product volume and the total cell volume. Mizrahi et al. (1975) concluded that electrical energy efficiency in a system could depend on the volumetric ratio of the product and immersion solution. By this way, their electrical energy efficiency was 0.4.

In current literature, there is limited information about the energy efficiency of the Ohmic blanching systems. Further work should be performed for the examination of energetic and also exergetic efficiency of these systems.

22.2.2 VOLUMETRIC REDUCTION

Ohmic blanching could cause volumetric reduction of the product and must be taken into account in the design of these systems. Available literature presents limited studies on volume reduction of food materials during Ohmic blanching.

Sensoy and Sastry (2004) compared the weight and volume loss of mushrooms during blanching under conventional and Ohmic heating conditions. During conventional heating, 5–7 min was required for samples to reach the maximum weight loss, 50% (Figure 22.1a). After the short heat treatment (40 and 47 s) in Ohmic blanching, 50% shrinkage was achieved at 30 s (Figure 22.1b,c). It is clear that by proper selection of operating conditions, Ohmic blanching can result in a faster heating rate. Due to volumetric heating, vegetables can be blanched without dicing in Ohmic blanching.

Further, Ohmic blanching does not require excess amounts of water while conventional blanching requires significantly larger amounts of water to transfer the necessary energy. Ohmic blanching merely requires sufficient water to achieve a continuous phase in the interstitial spaces between the mushrooms.

Sensoy and Sastry (2004) discussed that the predicted and experimental weight loss curves suggested that if the internal mushroom temperature was used, the predicted shrinkage was far lower than the measured value; however, if the water temperature was used, the results more closely matched experimental results. This indicates that nearly complete shrinkage is achieved during Ohmic blanching even though temperatures within the mushroom samples may be considerably lower than the normal blanching temperatures.

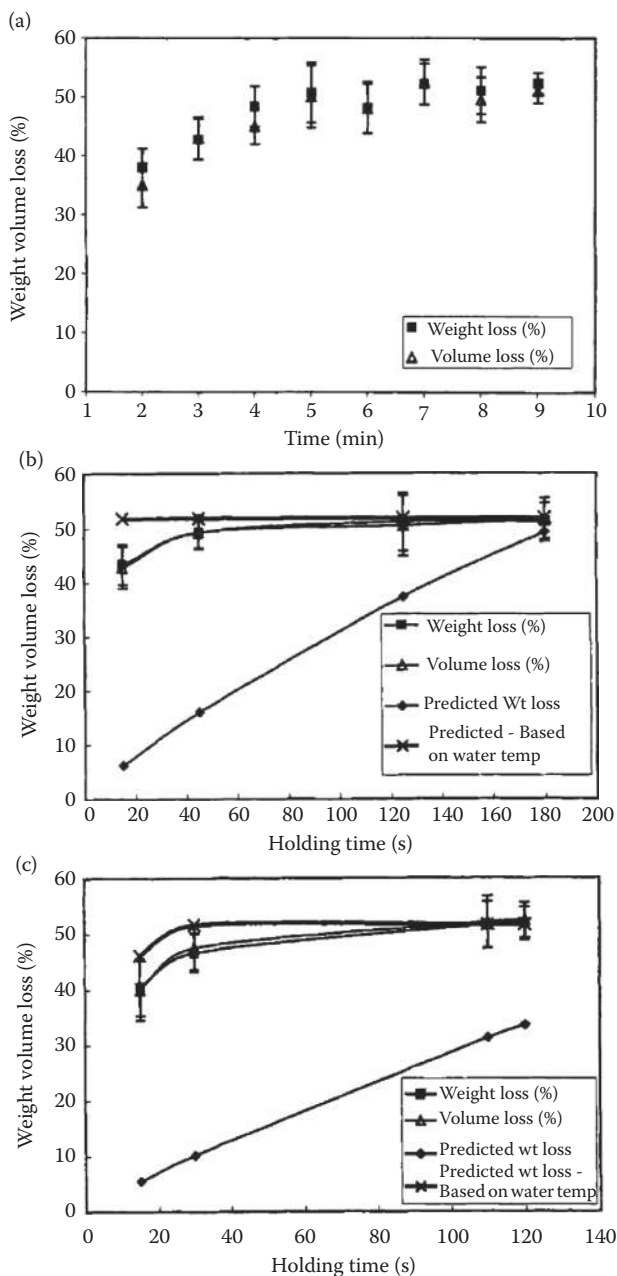


FIGURE 22.1 (a) Conventional blanching of mushroom caps in boiling water; (b) Weight/volume loss versus holding time after Ohmic blanching at 212 V for 40 s; (c) Weight/volume loss versus holding time after Ohmic blanching at 200 V for 47 s. (From Sensoy, I. and Sastry, S.K., *J Food Process Eng* 27: 1–15, 2004. With permission.)

22.2.3 SOLUTE LOSS

The extent of solute loss during blanching both Ohmically and with hot water follows the same pattern. It is proportional to the surface to volume ratio of the product and to the square root of the process time. Therefore, by eliminating the need for dicing, the Ohmic blanching may considerably

reduce the extent of solute leaching by a favorable combination of a low surface-to-volume ratio and a short blanching time, as compared to a hot water process.

To develop a relatively simple qualitative tool to analyze leaching losses during blanching, a simulation model can be beneficial to generate data. Mizrahi (1996) developed a model, which described the solute loss during Ohmic blanching of vegetables for a plate geometry. This model was formulated to allow charging of medium and product volume, initial solute concentration in the solid and in the product medium, partition factors, plate and medium temperature, external heat and mass transfer coefficients and sample (plate) thickness (Equations 22.6 and 22.7). The model is based on a process of unidirectional heat and mass transfer in an infinite plate that is divided into n layers of equal size. The momentary changes in the temperature and in the solute concentration were evaluated by calculating heat and mass transfer as well as energy and mass balance in each layer as follows (Mizrahi, 1996);

$$C_i^{t+\Delta t} = C_i^t + \frac{D^t \Delta t}{\delta^2} (C_{i+1}^t + C_{i-1}^t - 2C_i^t) \quad (22.6)$$

$$T_i^{t+\Delta t} = T_i^t + \frac{k^t \Delta t}{\delta^2 \rho C_p} (T_{i+1}^t + T_{i-1}^t - 2T_i^t) \quad (22.7)$$

where C is the solute concentration (w/v), T is the temperature, δ is the layer thickness, D is the solute diffusivity. ρ , C_p , and k are the density, the specific heat, and the thermal conductivity of the product, respectively. The subscript denotes the layer number (i) starting from the surface layer. The superscript denotes the time (t). At the surface, these two Equations 22.6 and 22.7 are modified to account for the surface heat (h) and mass (k_m) transfer coefficients as follows (Mizrahi, 1996):

$$C_i^{t+\Delta t} = C_i^t + \frac{D^t \Delta t}{\delta^2} (C_2^t - C_1^t) - \frac{k_m \Delta t}{\delta} (C_1^t - C_0^t) \quad (22.8)$$

$$T_i^{t+\Delta t} = T_i^t + \frac{h \Delta t}{\delta \rho C_p} (T_0^t - T_1^t) - \frac{k^t \Delta t}{\delta^2 \rho C_p} (T_1^t - T_2^t) \quad (22.9)$$

The extent of the solute loss (M_t) at any time (t) was calculated by subtracting the momentary solutes in the food from the initial one as follows:

$$M_t = A \left(C_{p0} L - \frac{\delta}{2} \sum_{i=1}^n C_i^t \right) \quad (22.10)$$

where A is the total surface area, C_{p0} is the initial solute concentration and L is the characteristic dimension (half-thickness) of the sample. The thermal conductivity of the blanching medium, which is changing as a function of the temperature, can be assumed to have the same value as water (Geankoplis, 2003);

$$k \text{ (Wm}^{-1}\text{K}^{-1}\text{)} = -0.6 + 0.00653T(\text{K}) - 8.3 \times 10^{-6} T^2 \quad (22.11)$$

The effect of the temperature on the diffusivity was evaluated by the Stokes–Einstein equation; having the following form:

$$\frac{D_m}{T} = \text{Constant} \quad (22.12)$$

where μ is the viscosity of the blanching water and can be expressed as

$$m(cp) = 0.001874 \exp \left[\frac{1849}{T(K)} \right] \quad (22.13)$$

This equation was obtained by curve fitting of water viscosity data and so the diffusivity of solutes evaluated by (Mizrahi, 1996):

$$D \text{ (m}^2\text{s}^{-1}\text{)} = \frac{0.93 \times 10^{-9} T}{\exp(1849/T)} \quad (22.14)$$

A range of values, as indicated, was used for the external film mass and heat-transfer coefficients. The rest of the equation parameters can be taken as those of water, namely density of 1000 (kg/m³) and specific heat of 4186 (J/kg°C). The extent of leaching can be written by a nondimensional form of M_t/M_∞ where M_∞ is the total amount of solutes leached at infinite time, namely at an equilibrium between the product and the medium. The value of M_∞ could be calculated from:

$$M_\infty = V_p (C_{p0} - C_{pf}) \quad (22.15)$$

According to model results, the average mass diffusivity in both cases was similar, such as $2.8 \times 10^{-9} \pm 1.3 \times 10^{-9}$ for conventional blanching and $2.9 \times 10^{-9} \pm 1.0 \times 10^{-9}$ for Ohmic blanching (Mizrahi, 1996). Table 22.2 shows the large difference in the extent of solute loss between Ohmic blanching and hot water blanching, when the former is carried out on the whole vegetable and the latter on the same vegetable after dicing.

Large vegetables having a relatively small surface-to-volume ratio could be blanched in a short time by Ohmic heating without any need for dicing them first. The energy dissipated by the electric current passing through the product, is capable of heating it uniformly and very fast regardless of its shape or size.

Kemp and Fryer (2007) investigated the enhancement of diffusion through foods using alternating electric fields. Figure 22.2 shows the images taken on a flatbed scanner for potato processed for duration of 350 and 750 s by conventional and electrical blanching treatments (electrical field strength of 815 V m⁻¹). The electrically processed potato appears to show a greater penetration of the dye, after 750 s of processing. This suggests that there is enhanced diffusion due to the electric field; however, at the same time structural changes have occurred in the potato during processing.

TABLE 22.2

Comparison of Solute Loss during Water Blanching and Ohmic Heating

Sample Mass (g)	Solute Loss after 2 min	Solute Loss after 4 min	Leaching Ratio (Water/Ohmic)	Average Leaching Ratio \pm SD
	Ohmic Heating ($M_{t=2 \text{ min}}$) (% of Total)	Water Blanching ($M_{t=4 \text{ min}}$) (% of Total)		
236	3.6	33.4	9.3	9.7 \pm 0.6
231	3	29.5	9.8	
242	4.5	40.5	9.0	
224	4.3	40.5	9.4	
235	3.8	40.9	10.8	

Source: From *J Food Eng*, 29, Mizrahi, S., Leaching of soluble solids during blanching of vegetables by Ohmic heating, 153–166, Copyright 1996, with permission from Elsevier.

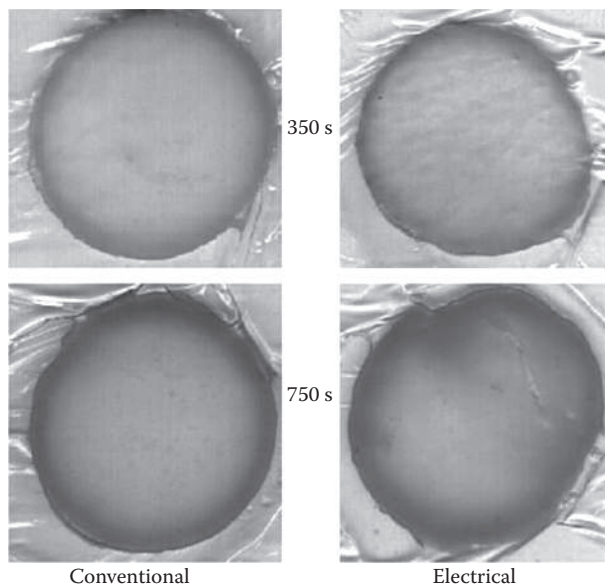


FIGURE 22.2 Images of potato cylinders with a diameter of 33 mm processed at 100°C for either 350 or 750 s in a 2.5 mM solution of rhodamine 6G, two processing techniques are shown here; electrical (815 V m⁻¹ field strength) and conventional. The images were captured using a flatbed scanner. (From *Innov Food Sci Emerg Technol*, 8(1), Kemp, M.R. and P.J. Fryer, Enhancement of diffusion through foods using alternating electric fields, 143–153. Copyright 2007, with permission from Elsevier.)

Thus, it is not possible to determine whether the differences in mass transfer result directly from the process used or indirectly that is, whether electrical and conventional processing leads to different rates of structural change and thus to different dye penetrations.

22.2.4 TEXTURE

The sensations during biting and chewing of a food material govern the overall acceptance or rejection of it by consumers. Thus, texture retention has become an important part of food processing research. It has also been proven that the texture of vegetables is greatly influenced by temperature and thermal processing (Anantheswaran et al., 1986). The high temperature may possibly cause heat damage or injury to the vegetable tissue, which may affect texture and structure of the food material. Structure and composition of cellular tissues mainly determine the texture of vegetables. The food industry needs reliable instrumental methods to measure the textural quality of fresh produce, and the industry also needs to ensure that they measure characteristics that are important to consumers.

Lespinaud et al. (2009) concluded that conventional blanching process results in higher textural deformation. Due to this, many microstructural studies have focused on the usage of alternative technologies for blanching. There is limited research on the effect of Ohmic blanching on the fruit/vegetable microstructure. Lemmens et al. (2009) evaluated the effect of different methods for blanching; conventional heating by using water bath until reaching the prescribed temperature, microwave heating at 1000 W, and Ohmic heating at 150 V and 50 Hz. All pretreated samples were cooked in 1 L water in a beaker on a hot plate (100°C for 20 min). They investigated the texture of the carrot pieces by the maximum force required to compress the samples to 70% of their original thickness; measured with a TA-XT2 Texture Analyzer (Stable Micro Systems, Surrey, UK). The mean value of the compression force of 10 carrot pieces is given as one single data point (Figure 22.3). Different heating techniques did not result in differences in textural attributes of carrot pieces.

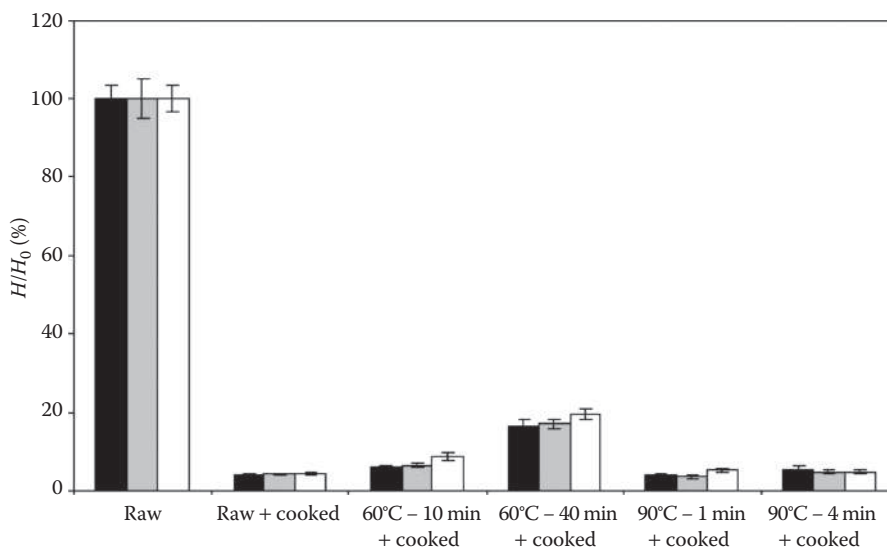


FIGURE 22.3 Effect of pretreatment conditions on the final texture of pretreated thermally processed carrot pieces. (v) Ohmic heating; (v) microwave heating; (≤) conventional heating. Raw = untreated samples; H_0 , Ohmic heating = 210 N; H_0 , microwave heating = 212 N; H_0 , conventional heating = 205 N. Error bars indicate the standard error. (From *Innov Food Sci Emerg Technol*, 10(4), Lemmens, L., Thermal pretreatments of carrot pieces using different heating techniques: Effect on quality related aspects, 522–529, Copyright 2009, with permission from Elsevier.)

This could be due to the dominating conductive heating caused by the blanching solution heating up as compared to the (limited) volumetric heating. However, no quantification regarding the mode of heat transfer was performed in this study and, hence, this explanation was only a suggestion for the observed data.

To visualize the difference between the high- and low-temperature blanched samples (beneficial effect on texture), a light microscope study of the samples was performed by Lemmens et al. (2009) that is presented in Figure 22.4. These results are in agreement with the results of the texture analysis. Low-temperature blanching preceding cooking seems to be the optimal blanching condition to retain the texture. Therefore, based on the other structural results, no clear difference between the different preheating techniques could be observed.

Praporscic et al. (2006) evaluated the effect of temperature and moderate electric field treatment under 100 V/cm on the textural structure of plant tissues (apple and potato) during Ohmic treatment. Figure 22.5 shows the force relaxation curves for potato and apple tissues when Ohmically heated at different electric field intensities and for freeze-thawed tissue (dashed lines). The total time for Ohmic blanching was 20 s. The apple tissue is rather soft, and the level of its cellular destruction (observed when the electric field exceeds 70 V/cm), is similar to the freeze-thawed tissue. The potato is texturally stronger, since it has a high starch content, which preserves the skeleton of the cells (Kaur et al., 2002). Consequently, its electrical treatment does not induce characteristics similar to that of the freeze-thawed tissue even at a value for voltage gradient at 100 V/cm. It can be concluded from data presented in Figure 22.5 that electric treatment less than 100 V/cm provides a high level of membrane destruction and mechanical softening of tissues. Previous researches (Lebovka et al., 2004a,b) showed that thermal damage is negligible for the treatment time of 20 s at a moderate temperature (<60°C). Therefore, changes in mechanical properties of studied tissues can be explained by electroporation.

Enhancement in mass transport due to electroporation has been discussed by Bazhal and Vorobiev (2000) as being due to two mechanisms: (1) electroporation of the cell membrane, and

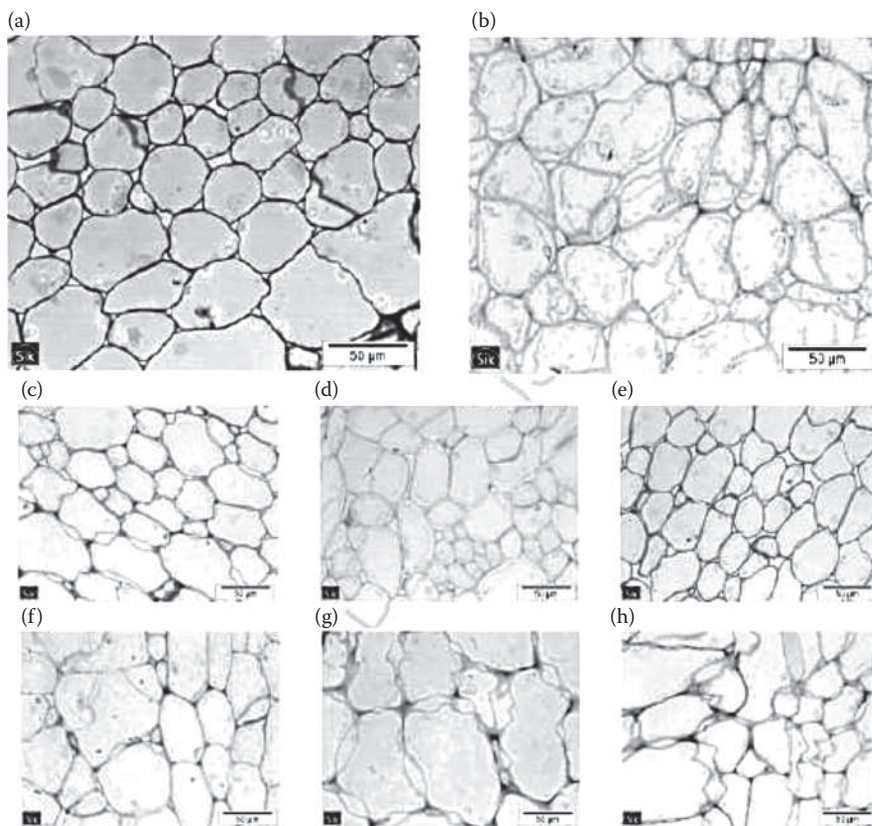


FIGURE 22.4 Microstructure of the carrot samples (magnification 20 \times). (a) Raw carrot; (b) Cooked carrot; (c) Con conventionally blanched (60°C – 40 min) + cooked carrot; (d) Ohmic blanched (60°C – 40 min) + cooked carrot; (e) Microwave blanched (60°C – 40 min) + cooked carrot; (f) Con conventionally blanched (90°C – 1 min) + cooked carrot; (g) Ohmic blanched (90°C – 1 min) + cooked carrot; (h) Microwave blanched (90°C – 1 min) + cooked carrot. (From *Innov Food Sci Emerg Technol*, 10(4), Lemmens, L., Thermal pretreatments of carrot pieces using different heating techniques: Effect on quality related aspects, 522–529, Copyright 2009, with permission from Elsevier.)

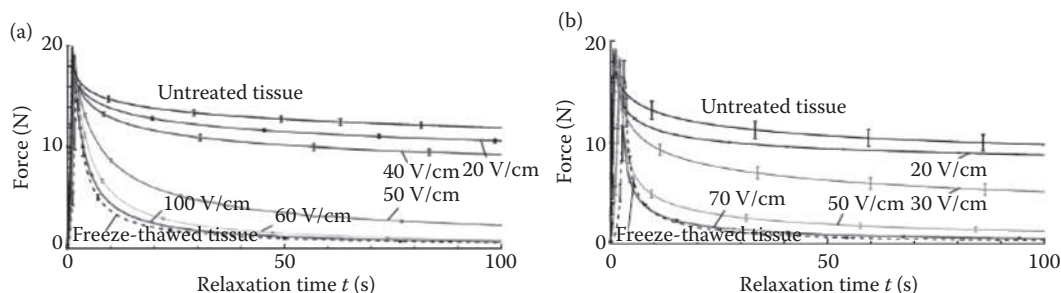


FIGURE 22.5 Textural relaxation curves (force F versus time t dependencies) for (a) potato and (b) apple tissues, Ohmically heated for 20 s by an alternative current at different values of electric field strength E ; dashed curves are for the freeze-thawed tissues. (From *Biosyst Eng*, 93(2), Praporscic, I. et al., Ohmically heated, enhanced expression of juice from apple and potato tissues, 199–204, Copyright 2006, with permission from Elsevier.)

(2) thermal denaturation of membranes. Under conditions of extremely limited heating, as for example with pulsed electric fields of microsecond durations, the former mechanism is expected to be dominant. Under conventional heating conditions, or high-frequency heating such as microwaves, the latter mechanism dominates. Under moderate, low-frequency treatments, such as Ohmic heating in the present case, both mechanisms may be operational. In particular, membranes undergo phase transitions and increase markedly in fluid at temperatures approaching an upper limit (Eze, 1990). While membrane effects are the critical factor in electroporation of microbial cells, plant cells also possess cell walls, composed largely of cellulose fiber, polysaccharides, and protein, which form an additional barrier to water diffusion. When no electric field is present, cell walls typically break down under thermal treatment, resulting in dramatic changes in physical properties (texture and electrical conductivity) in the 60–75°C temperature range (Andersson et al., 1994). When an electric field is applied, cell membrane permeabilization occurs at lower temperatures (Palaniappan and Sastry, 1991). At fields of 40 V/cm or greater, cell membrane permeabilization is essentially complete, and electrical conductivity becomes a linear function of temperature, as might occur with liquids. This process suggests that the cell wall is susceptible to electrical breakdown, although an understanding of the mechanism is not as developed as for lipid bilayer membranes. Furthermore, the reduction in treatment time also reduced the deformation of the sample structure, thereby improving sensory and textural qualities of the product.

The Ohmic heat treatment of apples and potatoes at electric field strength less than 100 V/cm allows a high level of membrane destruction and mechanical softening of tissues even at a moderate temperature of $T < 50^{\circ}\text{C}$. The results show that tissue disintegration depends on several treatment parameters (field intensity, temperature, and time duration) and type of plant tissue (Praporscic et al., 2006).

Eliot-Godereaux et al. (2002) investigated the stability of cauliflower in terms of textural attributes during Ohmic treatment. Cauliflower florets were sterilized in a 10 kW APV continuous Ohmic heating pilot plant with various configurations of pretreatments and processing conditions (Tables 22.3 and 22.4). The variations of textural parameters after precooking and Ohmic heating are presented in Figure 22.6. Ohmic heating treatments gave a product of attractive appearance, with interesting firmness properties and a high proportion of particles greater than 1 cm. Stabilities at 25°C and 37°C were verified, and in one case, the product was even stable at 55°C. Low-temperature precooking of cauliflower, high flow rate, and sufficient electrical conductivity of florets seem to be optimal conditions.

TABLE 22.3
Ohmic Processing Conditions for the Cauliflower

Run	$\sigma_{65^{\circ}\text{C}}^a$	Flow Rate (kg/h)	Processing Temperature ^b (°C)	Holding Length ^c	Minimum Holding Time ^d (s)	F_0^e
1	1.6	125	132	1–2	21	4.3
2	1.34	116	132	1–2	23	4.6
3	1.74	129	131	1–2	20	3.3
4	1.8	124	132	1–2	21	4.3

Source: From *Innov Food Sci Emerg Technol*, 2, Eliot-Godereaux, S.C., F. Zuber, and A. Goullieux, Processing and stabilisation of cauliflower by Ohmic heating technology, 279–287, Copyright 2002, with permission from Elsevier.

^a Electrical conductivities of mixture.

^b Measured at the end of holding tube.

^c Volume of bend(1):0.8 l (4.8 cm in diameter, 43.9 cm in length):volume of tube (2):0.63 l (4.8 cm in diameter, 35 cm in length).

^d Calculation based on a Newtonian laminar flow assumption.

^e Calculation based on $z = 10^{\circ}\text{C}$.

TABLE 22.4
Pretreatments for Cauliflower (25% w/w) to Be Processed Ohmically

Run	Pre-Treatments (w/w Concentrations)
1	Particles: 50°C, 5% NaCl, 30 min
2	Particles: 60°C, 2.2% NaCl, 20 min
3	Particles: 60°C, 4% NaCl, 20 min
4	Particles: 50°C, 3.5% NaCl, 30 min

Source: From *Innov Food Sci Emerg Technol*, 2, Eliot-Godereaux, S.C., F. Zuber, and A. Goullieux, Processing and stabilisation of cauliflower by Ohmic heating technology, 279–287, Copyright 2002, with permission from Elsevier.

The permeabilization of cells predominantly by electrical effects is desirable in maintaining relatively low temperatures, the effects of electrothermal treatments (microwave and Ohmic heating) at moderate levels has also been investigated by Wang and Sastry (2002). In comparing these two electrothermal pretreatments, frequency (60 Hz for Ohmic vs. 2450 MHz for microwaves) appeared to play an important role for the cell rupture. The lower frequency of Ohmic heating seemed to

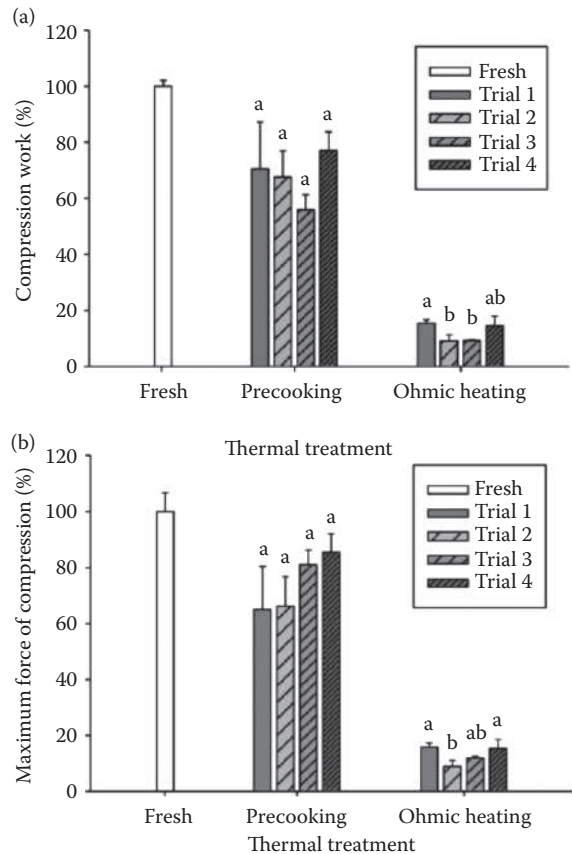


FIGURE 22.6 (a) Results of compression of cauliflower florets after various thermal treatments. (b) Maximum force of compression of cauliflower florets after various thermal treatments. (From *Innov Food Sci Emerg Technol*, 2, Eliot-Godereaux, S.C., F. Zuber, and A. Goullieux, Processing and stabilisation of cauliflower by Ohmic heating technology, 279–287, Copyright 2006, with permission from Elsevier.)

increase moisture diffusion across cell membranes to a greater extent. Also, it has been reported that thermal processing of vegetables may cause the rupture of cell walls (Hoff and Castro, 1969), loss of intercellular adhesion (Linehan and Hughes, 1969), and texture changes (Jaswal, 1969). These structural changes result not only in high moisture mobility but also softer tissues.

A comparison with the results of Lima and Sastry (1999) shows that the lower frequency (a 4 Hz sawtooth wave produced further enhancement, clearly indicating a frequency-related effect. It is thought that the frequency-related phenomenon occurs due to the capacitance of the cell membrane/wall complex: at high frequencies, charge buildup is not sufficient during a half-cycle to approach a critical membrane potential, but at low frequencies, sufficient time is available for charge buildup and electroporation to occur. The results of Bazhal and Vorobiev (2000) clearly indicate that with high-intensity electric field pulses, the electrical breakdown mechanism is dominant; although Ohmic heating is an unavoidable by-product of such a process.

22.2.5 COLOR

Changes in food color can be associated with its heat-treatment history. Various reactions such as pigment destruction and nonenzymatic browning reactions can occur during heating of fruits and vegetables and therefore can affect their color. Color can be used as a quality indicator to evaluate the extent of deterioration due to thermal processing (Avila and Silva, 1999). To examine color changes during Ohmic blanching treatment, color parameters (L, a, and b) and combinations of parameters could be useful, “-Lab,” “-b/a,” “-Lb/a,” hue angle, and so on. The combination of color parameters (“Lab,” “La/b,” etc.) is more effective than single tristimulus values to evaluate the overall color changes during thermal treatment (Ahmed et al., 2002). The blanching method affects the browning of purees (Table 22.5) (Icier et al., 2006). The color values—excluding “b” and “-Lab”—of water-blached samples have been statistically different than that of each puree when blanched Ohmically ($P < 0.01$) (Table 22.5). The “-b/a,” “-Lb/a” and hue angle values of water-blached pea puree were lower than only that of puree blanched by 20 V/cm. Icier et al. (2006) found that the effect of voltage gradients on the color of pea puree were statistically significant ($P < 0.01$). The Ohmic blanching for critical inactivation times by applying 40 and 50 V/cm voltage gradients resulted in similar color values and also a lesser browning than others. Icier et al. (2006) also investigated the color changes of Ohmic blanching at several holding times. To characterize the color changes of pea puree during Ohmic blanching, 20 V/cm was chosen as an example because of its long inactivation time and being able to observe the color changes practically. “-b/a,” “-Lb/a,” and “Hue angle” increased and “-a” decreased with the Ohmic blanching time.

The degradation of color during blanching of fruits and vegetables has been found to follow first-order reaction kinetics (Shin and Bhowmik, 1995; Avila and Silva, 1999; Ahmed et al., 2004).

$$\frac{C}{C_0} = \exp(kt) \quad (22.16)$$

It is not always possible to apply kinetics as simple as first order or zero order to describe the color changes since these changes cannot be only due to the Maillard reaction, but also due to the thermal destruction of pigments present in the samples (Ibarz et al., 1999). That is why a combined kinetics has been developed; a first stage of colored polymeric compound formation following a zero-order kinetics and the second stage supposes decomposition of the colored polymers into non-colored compounds following a first-order kinetics (Garza et al., 1999):

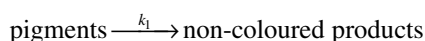
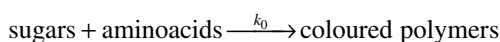


TABLE 22.5
The Color Values of Pea Purees Blanched at Critical Inactivation Times

Method	Voltage Gradient (V/cm)	L	-a	b	-b/a	-Lb/a	-Lab	Hue Angle
Fresh puree	—	52.30 ± 1.67 ^{ab}	12.12 ± 1.01 ^e	39.07 ± 2.88 ^{ab}	3.23 ± 0.11 ^e	168.8 ± 10.27 ^e	24795.3 ± 3165.7 ^e	72.77 ± 0.55 ^e
Ohmic blanching	20	55.89 ± 0.26 ^c	16.06 ± 0.48 ^d	39.88 ± 1.39 ^b	2.48 ± 0.03 ^a	138.8 ± 0.76 ^a	35809.9 ± 2243.8 ^{b,c}	68.07 ± 0.20 ^a
	30	53.51 ± 1.19 ^b	17.95 ± 0.48 ^c	38.72 ± 0.69 ^b	2.16 ± 0.04 ^c	115.5 ± 4.46 ^c	37208.3 ± 1734.6 ^b	65.13 ± 0.39 ^c
	40	51.77 ± 0.52 ^a	17.88 ± 0.36 ^c	36.44 ± 0.94 ^a	2.04 ± 0.05 ^d	105.5 ± 1.47 ^d	33731.2 ± 1220.1 ^c	63.87 ± 0.53 ^d
	50	53.84 ± 0.47 ^b	21.14 ± 0.19 ^a	43.15 ± 0.09 ^c	2.04 ± 0.01 ^d	109.9 ± 0.22 ^d	49123.7 ± 949.1 ^a	63.89 ± 0.16 ^d
Water blanching	—	57.79 ± 0.79 ^d	18.99 ± 0.30 ^b	42.37 ± 1.40 ^c	2.23 ± 0.04 ^b	128.9 ± 1.25 ^b	46487.8 ± 1620.2 ^a	65.85 ± 0.41 ^b

Source: From *J Food Eng*, 74, Icier, F., H. Yildiz, and T. Baysal, Peroxidase inactivation and color changes during Ohmic blanching of pea puree, 424–429, Copyright 2006, with permission from Elsevier.

^{a–e} For the same color parameter, mean values followed by the same letter are not significantly different ($P < 0.01$).

The changes for negative color values could be written as

$$\frac{dC}{dt} = k_{(0)} - k_{(1)}C \quad (22.17)$$

Equation 22.17 could be integrated with limited conditions for initial time:

$$C = C_0 \quad \text{at } t = 0 \quad (22.18)$$

The two-stage combining process expressed by Ibarz et al. (1999) was modified by Icier et al. (2006) as

$$C = \frac{k_{(0)}}{k_{(1)}} - \left(\frac{k_{(0)}}{k_{(1)}} - C_0 \right) \exp(-k_{(1)}t) \quad (22.19)$$

They obtained the color parameter, which accurately described the color change by first-order reaction kinetics, and then they applied the two-stage mechanism in kinetic modeling (Icier et al., 2006). Their results, including kinetic parameters for color change of pea puree during Ohmic blanching at 20 V/cm, are given in Table 22.6. They concluded that color parameters except “L” and “b” followed the first-order kinetics. The negative sign of the reaction constant was an indication of a decreasing trend. The regression coefficient was considered as the basis in selecting the appropriate combinations, which accurately described the first-order reaction. It was found that the Hue angle was the most appropriate combination (R^2 ; 0.954), which closely described the first-order reaction kinetics of total color changes of pea puree for Ohmic blanching at 20 V/cm. “-a” (R^2 ; 0.911), “-b/a” (R^2 ; 0.925), and “-Lb/a” (R^2 ; 0.911), were also adequate to describe the color degradation.

Vikram et al. (2005) evaluated the color changes of orange juice during electromagnetic and conventional heating. The activation values were 14.15 ± 0.63 kJ/mK for microwave, 79.92 ± 0.68 kJ/mK for Ohmic, and 53.31 ± 0.97 kJ/mK for infrared heating. The highest value was for Ohmic heating followed by infrared and the least was microwave. This may be due to the instantaneous heat generation in Ohmic heating due to the passage of current and higher dielectric properties of the juice. Higher activation energy implies that a smaller temperature change is needed to degrade color more rapidly.

TABLE 22.6
Kinetic Parameters for Color Change of Pea Puree during Ohmic Blanching at 20 V/cm

Color Parameter	k (min^{-1})	C_0	k_0 (min^{-1})	k_1 (min^{-1})	R^{2a}
L	-0.0038	55.79	—	—	0.272
-a	-0.0458	16.75	—	—	0.911
b	-0.0084	40.03	—	—	0.428
-b/a	0.0394	2.37	—	—	0.925
-Lb/a	0.0353	132.41	—	—	0.911
-Lab	-0.0563	37,271	—	—	0.869
Hue angle	0.0088	67.53	—	—	0.954
Hue angle ^b	—	67.39	1.2692	0.0088	0.935

Source: From *J Food Eng*, 74, Icier, F., H. Yildiz, and T. Baysal, Peroxidase inactivation and color changes during Ohmic blanching of pea puree, 424–429, Copyright 2006, with permission from Elsevier.

^a Nonlinear regression coefficient.

^b By using two-stage mechanism in a kinetic model.

22.2.6 VITAMINS AND PHENOLIC CONTENT

To predict the nutrient deterioration, the knowledge of the kinetics of vitamin C degradation including the reaction rate as a function of temperature of processing is required. The kinetics has been examined extensively in model systems with particular attention to intermediate moisture foods and during storage studies. It is necessary to study the effect of different processing temperatures on the retention of vitamins in the product and to use kinetic modeling to predict the losses during processing by different heating methods.

Castro et al. (2004) evaluated the ascorbic acid degradation of strawberries during Ohmic heating and compared them with the results of conventional heating processes. The obtained kinetic parameters were identical for the two types of heating processes leading to the conclusion that the presence of an electric field does not affect the ascorbic acid degradation (Table 22.7). The ascorbic acid degradation kinetics in strawberry industrial pulps for the temperature range of 60–97°C were unaffected by lower values of the electric field strength (20 V/cm). Ascorbic acid degradation followed first-order kinetics for both conventional and Ohmic heating treatments and the kinetic constants were in the range of the values reported in the literature for other food systems. The presence of an electric field does not affect ascorbic acid degradation. The reaction rate constants (k) and thermal resistance value (D) for vitamin C degradation during different methods of heating and at different temperatures are indicated in Table 22.8. The k value further confirmed the influence of temperature. The highest value was for microwave heating, due to internal heat generation and uncontrolled temperature increase. The next highest value was for Ohmic heating, followed by conventional and infrared heating. The higher value of activation energy for Ohmic heating is due to the higher dielectric properties of the juice and instantaneous heat generation due to the passage of electric current. Higher activation energy implies that a smaller temperature change is needed to degrade a specific compound more rapidly. The activation energy values varied with the method of heating. The values were 64.78 ± 2.63 kJ/mK for microwave; 47.27 ± 0.80 kJ/mK for Ohmic; 39.84 ± 0.61 kJ/mK for conventional and 37.12 ± 1.66 kJ/mK for infrared heating (Vikram et al., 2005). The variation in the activation energy values for the microwave heating was high ($SD = 2.63$ kJ/mK) indicating the non-uniformity of temperature during processing. This further strengthens the fact that vegetables are sensitive to higher temperatures and higher vitamin C deterioration occurs at higher temperatures of above 100°C. Vikram et al. (2005) concluded that the heating method had a definite influence on the retention of vitamin C during thermal treatment. During thermal treatments, temperature had

TABLE 22.7
Kinetic Parameters of Thermal Degradation of Ascorbic Acid in Strawberry Pulp

Temperature (°C)	60	70	75	80	90	97
$D_{\text{conventional}}$ (min)	294	196	175	152	123	111
r^2	0.999	0.981	0.986	0.998	0.993	0.991
D_{Ohmic} (min)	256	192	169	154	130	114
r^2	0.987	0.980	0.985	0.981	0.995	0.988
$z_{\text{conventional}}$ (°C)	46.73 ($r^2 = 0.995$)					
z_{Ohmic} (°C)	46.73 ($r^2 = 0.999$)					
$K_{o \text{ conventional}}$ (s ⁻¹)	0.15 ($r^2 = 0.986$)					
$K_{o \text{ Ohmic}}$ (s ⁻¹)	0.14 ($r^2 = 0.991$)					
$E_{a \text{ conventional}}$ (kJ mol ⁻¹)	21.36					
$E_{a \text{ Ohmic}}$ (kJ mol ⁻¹)	21.05					

Source: From *J Food Sci*, 69(9), Castro, I. et al., The effect of electric field on important foodprocessing enzymes: Comparison of inactivation kinetics under conventional and Ohmic heating, 696–701, Copyright 2004, with permission from Elsevier.

TABLE 22.8
Rate Constant and Thermal Resistance Parameters for Vitamin C Degradation

Heating Method	Temperature (°C)	<i>k</i> -Value (min ⁻¹)	<i>D</i> -Value (min)
Conventional	50	0.0351	65.67
	60	0.0462	49.81
	75	0.0852	27.02
	90	0.1784	12.91
Ohmic	50	0.0240	95.96
	60	0.0393	58.55
	75	0.0971	23.72
	90	0.1571	14.66
Infrared	50	0.0444	51.91
	60	0.0760	30.32
	75	0.0969	23.76
	90	0.2284	10.08
Microwave	100	0.0504	45.69

Source: From *J Food Eng*, 69, Vikram, V.B., M.N. Ramesh, and S.G. Prapulla, Thermal degradation kinetics of nutrients in orange juice heated by electromagnetic and conventional methods, 31–40, Copyright 2005, with permission from Elsevier.

a greater influence and the degradation was rapid at higher temperatures. Ohmic heating was the most rapid followed by microwave, and infrared heating. The conventional method had a longer lag period and the time to reach the targeted temperature was about 5 min. Though Ohmic heating was rapid, the temperature controller built into the system monitored the temperature within the range of targeted temperatures. Ohmic heating indicated lower degradation of vitamin C than microwave and infrared heating. Of the four methods studied (Ohmic, infrared, microwave, and conventional) Ohmic heating resulted in the maximum retention of vitamin C. The degradation was highest in microwave, which may be attributed to uncontrolled temperatures generated during processing, which exceeded 100°C reaching 125°C and due to the heat-labile nature of vitamin C.

In another study that was performed by Icier (2010), artichoke by-product (from outer bracts and stems) was pretreated with Ohmic blanching (25 and 40 V/cm, at 85°C) and water blanching (at 85°C and 100°C). At the same blanching temperature, Ohmic blanching by 25 V/cm and water blanching showed similar total phenolic content retentions (Table 22.9). The retentions of vitamin C and the total phenolic contents were found to be the highest in the by-product blanched Ohmically by 40 V/cm

TABLE 22.9
Effects of Blanching on Vitamin C Content and Total Phenolic Content of Artichoke By-Product

Blanching Method	Voltage Gradient (V/cm)	Blanching Temperature (°C)	Vitamin C Loss (%)	Total Phenolic Content Retention (%)
Ohmic blanching	25	85	63.13	62.94
	30	85	65.80	74.82
	40	85	48.02	89.14
Water blanching	—	85	71.19	64.97
	—	100	47.39	50.21

Source: From Icier, F., *J Food Process Eng* 33(4):661–683, 2010. With permission.

voltage gradient at 85°C. Furthermore, Ohmic blanching by 40 V/cm caused similar vitamin C loss in addition to faster enzyme inactivation and higher total phenolics content retention at the lower temperature, than water blanching.

22.2.7 ENZYME ACTIVITY

Endogenous enzymes in raw food ingredients may have beneficial or detrimental effects on the nutritional, functional–sensorial properties of the derived feeds. The questions surrounding thermal deactivation of enzymes is therefore of strong interest for food scientists, with the scope of better descriptions of the time course of the phenomenon and understanding of the relevant mechanisms. A similar concern exists in food technology when an enzyme is used at a certain step of an industrial process, with the need to “kill” the catalyst at a further step. This explains the large number of works devoted to the description of the deactivation of enzymes during the past three decades. In food processing, a heating treatment is often used to deactivate the appropriate enzymes (Yemenicioglu et al., 1998). Indicator enzymes can be used to determine the blanching efficiency of fruit and vegetables; such as peroxidase, polyphenoloxidase, and lipoxigenase.

Peroxidases (PODs) are used as blanching indicators since they belong to the most stable and widespread plant enzymes and have a certain effect on the loss of color and textural changes of fruits and vegetables (Yemenicioglu et al., 1998; Forsyth et al., 1999; Icier et al., 2006). Their advantage compared to other potential blanching index enzymes is a simple, inexpensive activity measurement (Khan and Robinson, 1993; Tijskens et al., 1997; Yemenicioglu et al., 1998; Forsyth et al., 1999; Icier et al., 2006). The primary function of POD in plants is the reduction of hydrogen peroxide at the expense of oxidation of phenolic compounds. It is responsible for the mechanical properties of cell walls during extension, cell adhesion, and disease resistance (Tijskens et al., 1997). The presence of an electric field can influence biochemical reactions by changing molecular spacing and increasing interchain reactions (Castro et al., 2004). During Ohmic blanching, in addition to heat effects, electrical effects might also inactivate enzymes in a short time rather than conventional blanching. Although there are several studies on the inactivation of POD during thermal treatments, only limited studies (Icier et al., 2006; Lemmens et al., 2009) have been conducted on the inactivation of POD during Ohmic blanching of pea puree samples. Icier et al. (2006) performed Ohmic blanching processes by applying four different voltage gradients (20, 30, 40, and 50 V/cm). The puree samples were heated from 30°C to 100°C and held at 100°C to achieve adequate blanching. The conventional blanching was performed at 100°C in a water bath. The critical inactivation times of peroxidase in pea purees blanched Ohmically and conventionally, are represented in Table 22.10.

TABLE 22.10
The Critical Inactivation Times of Peroxidase in Pea Purees Blanched Ohmically and Conventionally

Blanching Method	Voltage Gradient (V/cm)	Heating Time (s) (30–100°C)	Holding Time at 100°C (s)	Critical Inactivation Time (s)
Ohmic blanching	20	516	60	576 ^a
	30	141	60	201 ^b
	40	74	30	104 ^c
	50	54	0	54 ^d
Water blanching	—	—	300	300 ^e

Source: From *J Food Eng*, 74, Icier, F., H. Yildiz, and T. Baysal, Peroxidase inactivation and color changes during Ohmic blanching of pea puree, 424–429, Copyright 2006, with permission from Elsevier.

^{a–e} For the same column, values followed by the different letter are statistically different (two-tailed pooled *t*-test, $P \leq 0.01$).

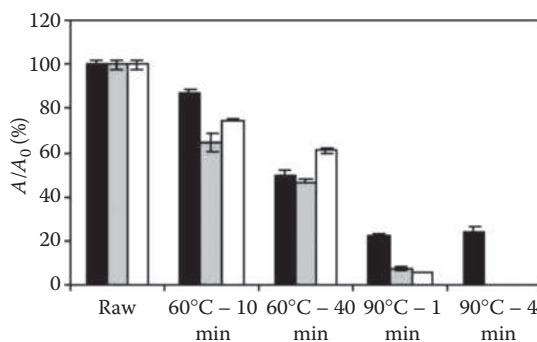


FIGURE 22.7 Residual POD activity of the carrot samples after different pretreatments. (v) Ohmic heating; (v) microwave heating; (≤) conventional heating. Raw = untreated sample; $A_0 = 1.04$ U POD/g carrot. Error bars indicate the standard deviation. (From *Innov Food Sci Emerg Technol*, 10(4), Lemmens, L., Thermal pretreatments of carrot pieces using different heating techniques: Effect on quality related aspects, 522–529, Copyright 2009, with permission from Elsevier.)

Critical inactivation time decreases as the voltage gradient increases. Furthermore, critical inactivation time for water blanching is longer than that for Ohmic blanching ($P < 0.01$). At high voltage gradients the electrical current passing through the samples was higher and the effect of the voltage gradient on the POD inactivation was statistically different ($P < 0.01$). Below 30 V/cm, the energy dissipated during Ohmic blanching was lower than water blanching, so the longer inactivation time was achieved at 20 V/cm.

In an other study that was carried out by Lemmens et al. (2009), the effect of Ohmic blanching on the POD and PME activity of carrot pieces has been determined (relative to the enzyme activity in the raw sample (A_0)) and it was represented in Figure 22.7. Generally, from the results, it can be stated that no unambiguous difference between the different heating techniques could be observed, except for Ohmic blanching at high temperatures. These treatments seem to retain higher residual enzyme activities than the same treatments with other blanching techniques. The reason for this is unknown, but most likely, it will be associated with nonuniformity in temperature distribution during heating.

Another important enzyme, which corresponds as an indicator enzyme to determine necessary blanching condition (time and temperature combination), is lipoxygenase (LOX). It is an enzyme found in many plants and animals and catalyzes the oxygenation of polyunsaturated fatty acids (PUFA) to form fatty acid hydroperoxides. In many applications it is possible to use crude plant materials or extracts, but such materials usually contain multiple enzymes that may reduce polyunsaturated fatty acid substrate availability or metabolize the hydroperoxide products, thereby modulating lipoxygenase action, which has led to understand the activities and properties of plant and other lipoxygenases as food processing additives and to remove selectively specific lipoxygenase from plants based on such understanding (Casey et al., 1996). To the best of authors' knowledge, in current literature there were no studies conducted regarding the inactivation of the LOX during Ohmic blanching.

PPO (E.C.1.14.18.1) is an oxidoreductase enzyme and contains copper. PPO causes browning by catalyzing the oxidation of monophenolic compounds to *o*-diphenols and *o*-dihydroxy compounds to *o*-kinons (Van Loey et al., 2002). This metallo-enzyme, which is widely distributed in plants, is considered to be the main contributor to browning, discoloration, and darkening in fruits and vegetables (Billaud et al., 2004). Enzymatic browning can be inhibited by using chemicals such as ascorbic acid, sulfites, sodium diethyl dithiocarbamate, and so on, or heat treatment (Ilhami et al., 2005). The deactivation of PPO by thermal treatment has been reported as the most effective method to control enzymatic browning (Weemaes et al. 1998). Tate et al. (1964) have suggested that heat deactivation

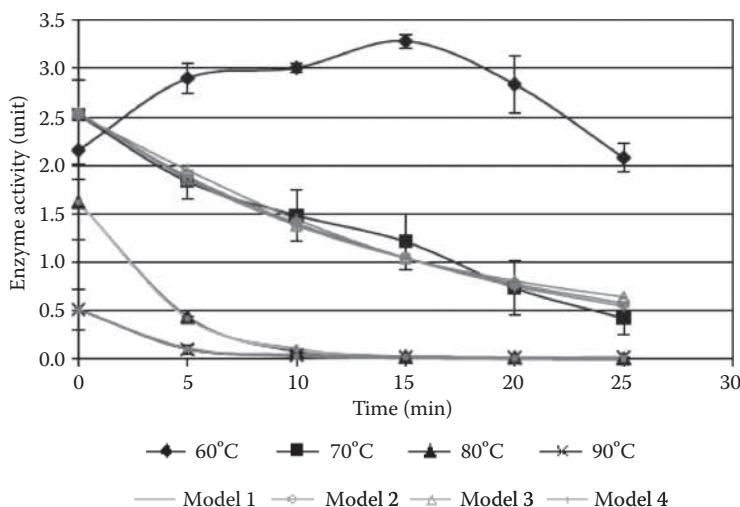


FIGURE 22.8 The inactivation curves of PPO at different Ohmic holding temperatures at 30 V/cm. (From *J Food Eng*, 85, Icier, F., H. Yildiz, and T. Baysal, Polyphenoloxidase deactivation kinetics during Ohmic heating of grape juice. 410–417, Copyright 2008, with permission from Elsevier.)

treatments should be rapid since slow blanching processes might result in activation of the PPO in the plant tissue rather than deactivation. Icier et al. (2008) reported that as the Ohmic holding temperature increased, the deactivation of the PPO enzyme increased for the same holding time (Figure 22.8). The effect of temperature, holding time, and their interaction on the activity of PPO was significant ($P < 0.05$). For the temperature range of 70–90°C, similar deactivation curves were obtained in recent studies; for glucoamylase in Polakovic and Bryjak (2002), for urease in Illeova et al. (2003), for β -galactosidase in Ladero et al. (2005). Castro et al. (2004) suggested that the presence of the electric field might remove the metallic prosthetic groups present in the PPO enzyme, thus causing the enhancement of enzyme activity loss. Similarly Giner et al. (2005) suggested that any increase of the electric field would yield considerable improvement in the effectiveness of pulsed electric field treatments in reducing pectinesterase activity. Icier et al. (2008) reported that, for the temperature range studied, the using of a one step first-order model to a totally deactivated product proved adequate. The use of more complex models did not improve the fits and it was concluded that the simplest first-order kinetics model was adequate to describe the PPO deactivation in grape juice by Ohmic heating. The inactivation of enzymes during Ohmic heating could give useful insight for the design of the critical inactivation time/temperature combinations of fruits and vegetables during Ohmic blanching.

22.3 FACTORS AFFECTING OHMIC BLANCHING

In the current literature there were limited studies (Mizrahi et al., 1975; Mizrahi, 1996; Icier et al., 2006; Kulshrestha and Sastry, 2006; Lemmens et al., 2009; Allali et al., 2010; Icier, 2010) conducted on the application of Ohmic blanching on fruits and vegetables (Table 22.1). In all these studies, as discussed above, generally selected quality attributes were investigated. System parameters affecting the performance of the system such as applied voltage gradient, type of current, frequency, waveform, and electrical conductivity of the sample are discussed in this section.

22.3.1 ELECTRICAL CONDUCTIVITY

The key to the successful implementation of an Ohmic process was knowledge on the rate of heat generation and the overall electrical conductivity changes of the food material (Leizeron and

Shimoni, 2005; Bozkurt and Icier, 2009). As mentioned in recent research (Marra et al., 2009), it was crucial to evaluate the influence of key variables such as electrical field strength and sample conductivity to ensure a completely safe Ohmically treated product.

For particulate foods, it has been observed that most vegetables and meats have lower electrical conductivities than liquids (Tulsiyan et al., 2008). In an Ohmic heating process for particulate foods, thermo desirable situation is that, in which the electrical conductivities of fluid and solid particles are equal (Wang and Sastry, 1993a). From the safety point of view, it is important to determine the worst-case scenario, and this is most likely associated with undetected low-conductivity particles in the system. The increase in electrical conductivity by increasing the electrolytic content of foods may be accomplished by salt infusion via soaking or blanching of solids in salt solution. This may be used as a pretreatment for Ohmic heating of particulate foods to obtain uniform heat treatment, if the composition and other properties of the food are not greatly affected (Palaniappan and Sastry, 1991; Wang and Sastry, 1993a,b). On adjusting the electrical properties of different components, it may be possible to ensure that uniform heating within the product takes place. If electro-permeabilization occurs in a vegetable tissue, the apparent dielectric constant and conductance should be affected due to the changes in membrane permeability. The permeability of cell membranes has long been measured by the electrical conductivity of the tissue. Sarang et al. (2007) developed a blanching method for increasing the ionic content in solid particulates and adjusting the electrical conductivities of the solid components to liquid sauce. By adjusting blanching times for each constitute of the mix, it may be possible to uniformly blanch the entire product.

22.3.2 VOLTAGE GRADIENT

Another important system parameter is the applied voltage gradient. In Ohmic treatments, the rate of heating is directly proportional to the square of the electric field strength and the electrical conductivity (Sastry and Li, 1996). At high-voltage gradients, the electrical current passing through the samples was higher and higher structural deformation was observed within the sample. Also, the energy dissipated by the electric current passing through the samples was capable of heating it uniformly and very fast, regardless of its shape or size. The increase in generated energy would result in lower treatment times, but at this point, also taken into consideration should be the metal migration from electrode surface, microbial load of the sample, and so on.

The electric field strength is effective on the extraction yield (Table 22.11). Increasing the electrical field strength from 60 to 100 V/cm increases the extraction yield for different moisture contents. This phenomenon was most pronounced with raw bran. This finding is significant because enhanced extractions are thought to be due in part to a rise in temperature (Lima et al., 2001), but no such temperature increase has been observed in the case of raw bran (Lakkakula et al., 2004). This finding

TABLE 22.11

Effect of Electric Field Strength and Moisture Content on Rice Bran Oil Yield (60 Hz)

Moisture Content	Electric Field Strength		
	60 V/cm	100 V/cm	140 V/cm
10.5%	49.44 ± 0.34% ^x	71.05 ± 8.39% ^y	75.88 ± 5.98% ^y
21%	64.33 ± 0.31% ^x	72.18 ± 2.44% ^y	74.27 ± 0.86% ^y
30%	82.63 ± 0.16% ^x	83.89 ± 0.5% ^y	77.23 ± 2.38% ^z

Source: From *Bioresource Technol*, 92, Lakkakula, N.R., M. Lima, and T. Walker, Rice bran stabilization and rice bran oil extraction using Ohmic heating, 157–161, Copyright 2004, with permission from Elsevier.

Note: Means within a row with different superscript letters (x, y, z) are different ($P \leq 0.05$).

could be important for processes that involve the extraction of heat labile components. Increasing the electrical field strength from 100 to 140 V/cm does not significantly increase the amount of oil extracted (it slightly decreased at 30% moisture content). This suggests that there exists optimal electrical field strength for extraction, and providing higher field strength beyond this optimum does not significantly impact the amount of oil extracted. This phenomenon was also observed by Zhong and Lima (2003), who found that electrical field strength and endpoint temperature significantly impacted the vacuum drying rate of sweet potato, and that optimal values existed for each treatment parameter.

22.3.3 FREQUENCY AND WAVEFORM

It is known that alternating current creates an oscillatory movement of ions, which generates the heat dissipation underlying the resistance-heating phenomenon, whereas most Ohmic heating systems have used 50–60 Hz alternating current. Altering the frequency and waveform of alternating current during Ohmic heating has been shown to influence the heat and mass transfer properties of foods, which would affect the efficiency of extraction and the heating rate. Lima et al. (1999b) investigated the effect of frequency (4, 10, 25, and 60 Hz) and waveform (square, sine, and sawtooth) on the electrical conductivity–temperature profiles of turnip tissue during Ohmic treatment (Table 22.12). They discussed that, for all frequencies except 4 Hz, a very slow increase in temperature occurred until a critical time, after which the temperature increased dramatically. The heating rate after this critical time has been reported as the same for all frequencies and occurred at approximately 60°C. The time for the center of the turnip to reach 100°C increased as the frequency increased, and a dramatic increase in temperature followed a slow temperature increase. The decrease in heating rate has been observed at approximately 55°C with the 4 Hz sine and sawtooth waves, but not with the square wave.

TABLE 22.12

Mean Values of $\sigma \pm 1$ Standard Deviation at Selected Temperatures for Different Wave Forms

Wave Form	Frequency (Hz)	Temperature (°C)			
		30	50	75	95
Sine wave	4	0.433 \pm 0.052 ^{ax}	0.794 \pm 0.169 ^{ax}	1.31 \pm 0.228 ^{ax}	1.70 \pm 0.217 ^{ax}
	10	0.107 \pm 0.039 ^{bx}	0.406 \pm 0.067 ^{bx}	0.778 \pm 0.119 ^{bx}	0.961 \pm 0.114 ^{bx}
	25	0.059 \pm 0.017 ^{bx}	0.404 \pm 0.137 ^{bx}	0.956 \pm 0.237 ^{bx}	1.22 \pm 0.242 ^{bx}
	60	0.033 \pm 0.004 ^{cx}	0.318 \pm 0.164 ^{bx}	0.758 \pm 0.249 ^{bx}	0.967 \pm 0.243 ^{bx}
Sawtooth wave	4	0.474 \pm 0.073 ^{bx}	1.04 \pm 0.155 ^{ay}	1.540 \pm 0.142 ^{ax}	1.82 \pm 0.122 ^a
	10	0.165 \pm 0.054 ^{bx}	0.457 \pm 0.097 ^{bx}	0.780 \pm 0.155 ^{bx}	0.965 \pm 0.199 ^{bx}
	25	0.087 \pm 0.021 ^{by}	0.408 \pm 0.106 ^{bx}	0.811 \pm 0.193 ^{bx}	0.983 \pm 0.186 ^{bx}
	60	0.039 \pm 0.003 ^{cx}	0.418 \pm 0.159 ^{bx}	0.794 \pm 0.243 ^{bx}	0.962 \pm 0.265 ^{bx}
Square wave	4	0.048 \pm 0.023 ^{ay}	0.233 \pm 0.140 ^{az}	0.554 \pm 0.224 ^{ay}	0.769 \pm 0.243 ^{ay}
	10	0.042 \pm 0.014 ^{by}	0.167 \pm 0.060 ^{ay}	0.432 \pm 0.070 ^{by}	0.646 \pm 0.033 ^{ay}
	25	0.038 \pm 0.011 ^{az}	0.257 \pm 0.162 ^{ay}	0.583 \pm 0.170 ^{by}	0.789 \pm 0.130 ^{ay}
	60	0.042 \pm 0.017 ^{ax}	0.217 \pm 0.065 ^{ax}	0.603 \pm 0.148 ^{ax}	0.853 \pm 0.155 ^{ax}

Source: From Lima, M., Heskitt, B.F., and Sastry, S.K., *J Food Process Eng* 22:41–54, 1999a. With permission.

^{a–c} For the same temperature, values followed by the same letter are not statistically different (two-tailed pooled *t*-test, $P \leq 0.05$).

^{x–z} For the same frequency and temperature, values followed by the same letter or are statistically different (two-tailed pooled *t*-test, $P \leq 0.05$).

Imai et al. (1995) found that as frequency was increased from 50 to 10,000 Hz, the time required for a Japanese radish sample center to reach 80°C, increased approximately sixfold. They reported that the same heating rate occurred above 60°C and was independent of frequency. However, they also found that the higher the frequency, the longer the critical time before the heating rate increased. They concluded that the lower frequencies of Ohmic heating damaged the cell membranes, as pressurizing the radish to damage the cell membranes resulted in the immediate fast heating rate. Electroporation is thought to occur under electrical field strengths in the range of hundreds of volts per centimeter, and results in cell membranes becoming permeable (Farkas, 1989). This phenomenon can be reversible, in which the cell membranes revert to their original structure when the electric field is removed, or irreversible under critically high electric field strength, in which cell membranes are damaged or destroyed. The dramatic temperature increase occurred immediately at 4 Hz for sine and sawtooth waves, and with a minimal delay for a square wave, possibly indicating a change in cellular structure, which resulted in a decreased resistance to current flow and increased moisture transport.

Electro-osmosis has been proposed by Halden et al. (1990) and Schreier et al. (1993) respectively, to explain the increase in electrical conductivity and dye diffusion observed when comparing Ohmic heating with conventional heating. This phenomenon involves the increased diffusion of materials across cell membranes by virtue of an applied electric field. Experiments conducted by Kim and Pyun (1995) and Imai et al. (1995) suggest that the frequency of alternating current affects the efficiency of extraction and the heating rate. The electro-permeabilization occurring in a vegetable tissue would result in a change in the apparent dielectric constant and conductance. Due to the change in membrane permeability, a linear change in electrical conductivity is observed, thus, lower treatment times than those used in conventional methods can be employed. This behavior could be beneficial in obtaining a sample with higher nutritional, sensory, and quality attributes while blanching of fruits and vegetables Ohmically.

The heating rate increases as frequency decreases (Lima and Sastry, 1999). The effect of frequency and waveform of alternating current applied during Ohmic pretreatment is significant, with the highest post drying rates obtained with the lower frequency and sawtooth waveform. The efficiency of mass transfer processes appears to be significantly dependent on waveform and frequency of alternating current.

Lakkakula et al. (2004) evaluated the effect of electric field and frequency on the extraction yield of rice bran during Ohmic treatment. The effect of frequency on oil extraction yield (at 60 V/cm) has been studied at different moisture contents. The results, summarized in Figure 22.9, showed that at all moisture levels, Ohmic heating using an alternating current of 1 Hz yield significantly more oil than Ohmic heating conducted at 60 Hz ($P < 0.05$). During Ohmic heating, the electric field may cause changes in the permeability of cell membranes of plant cells below the temperature at which membranes are permeabilized due to thermal effects (Kulshrestha and Sastry, 2006). Diffusion is

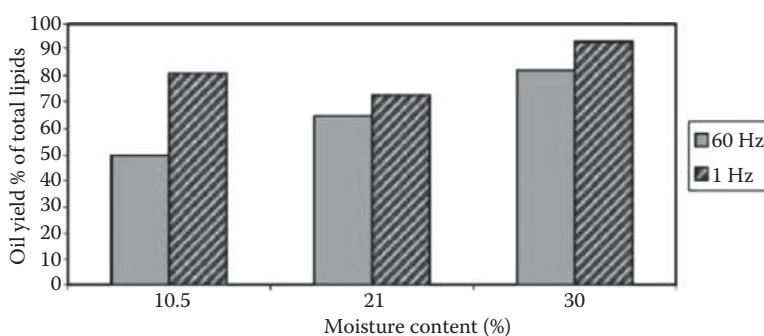


FIGURE 22.9 Effect of frequency on yield. (From *Bioresource Technol.* 92, Lakkakula, N.R., M. Lima, and T. Walker, Rice bran stabilization and rice bran oil extraction using Ohmic heating, 157–161, Copyright 2004, with permission from Elsevier.)

enhanced, electrical conductivity changes are more linear during heating, and moisture migrates more easily out of the tissue (Halden et al., 1990). Thus, Ohmic pretreatment has been found useful in blanching and extraction processes of fruits and vegetables.

22.4 CONCLUDING REMARKS

As a rapid blanching method, Ohmic blanching offers a considerable advantage over conventional heating methods, particularly in big particulate foods in which heat transfer is predominantly governed by conduction. However, even with this major advantage and the fact that this technology has been available for many years, its adaptation by industry has been relatively slow. This lack of interest to date may be largely due to:

1. A lack of available in-depth information on areas such as its impact on all aspects of product quality. Recent years have shown a substantial number of publications in the area of the quality of Ohmically blanched processed samples, but this needs to be replicated across a wider range of food commodities. The availability of such information will help to convince processors of the benefits of this technology.
2. As a potential blanching technique, more work needs to be published on the effectiveness of Ohmic blanching for inactivating microorganisms and its impact on product quality and shelf life. However, in addition to this a greater understanding of temperature distribution within products needs to be developed. Conventional heating methods are generally well understood in this context and until similar knowledge is available for Ohmic blanching, food processors charged with consumer safety are going to be cautious to change from the methods they are most familiar with.
3. Needs in designing and scaling-up larger systems for industrial application. This step is essential in order to evaluate the actual capital costs for initial installations and to estimate the energy costs involved in particular treatments, in order to further investigate the efficiency and economics of Ohmic blanching processing.
4. A continuing need for the production of more dielectric property data on foodstuffs and potential packaging. This information is the key to improving the understanding of temperature distribution and is also important in the design of Ohmic blanching systems.
5. Mathematical modeling improves the understanding of Ohmic blanching of food and it is essential to the continued development of this technology. More efforts are needed in order to develop computer-aided engineering of the processes and plants on an industrial scale.

NOMENCLATURE

SYMBOLS

A	total surface area (m^2)
C	solute concentration (w/v)
C_p	specific heat ($\text{kJ/kg}^\circ\text{C}$)
D	solute diffusivity (m^2/s)
E_a	activation energy (kJ/mol)
G	volumetric flow rate (m^3/s)
h	convective heat-transfer coefficient ($\text{W/m}^2\text{K}$)
I	current (A)
k	thermal conductivity (W/mK) or first-order reaction rate constant (min^{-1})
k_m	mass transfer coefficient (m/s)

K	kinetic parameter (1/s)
L	the distance between electrodes or characteristic dimension in Equation 22.13
n	layer of equal size
r	regression coefficient
t	time (s)
T	temperature (°C or K)
V	voltage, (V)
z	kinetic parameter (°C)

SUBSCRIPTS

B	blanching
c	come up time
e	the surface area of electrode surface
i	initial
p	product
p_o	initial solute concentration
p_f	final solute concentration
r	residence time of product through the system
s	system
∞	infinite

GREEK LETTERS

σ	electrical conductivity (S/m)
ρ	density (kg/m ³)
δ	layer thickness
μ	viscosity

ABBREVIATIONS

LOX	lipoxigenase
POD	polyphenoloxidase
PPO	peroxidase

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23 Ohmic Heating as Thawing and Tempering Technology

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23.1 INTRODUCTION

Freezing of foods has been a common way of long-term food preservation for thousands of years because of the high product quality and long shelf life. During freezing, water is converted into ice and the formation of ice removes water from food systems. The reduced water activity helps to preserve foods for longer periods of time, and freezing temperatures reduce the rate of chemical reactions and the activity of microorganisms and enzymes, thereby extending the storage life of frozen foods. The nutritional quality of the food is also preserved better by freezing. It is known that the least vitamin loss occurs in frozen food preservation. The loss of quality of frozen foods mainly depends on packaging, storage temperature, length of storage time, and thawing procedure. Frozen foods are usually stored at -18°C , so thawing or tempering is needed for further processing or cooking. However, chemical, physical, and microbiological changes that occur during long thawing or tempering periods result in unacceptable changes in product quality. Therefore, selection of methods that shorten the thawing or tempering process and, in consequence, maximize the safety and quality retention of foods, are important for frozen food industry. The novel thawing methods are microwave thawing, high-pressure thawing, acoustic thawing, and Ohmic thawing. These innovative thawing methods can shorten thawing time, thus reducing drip loss and improving product quality (Li and Sun, 2002). Ohmic thawing has advantages over conventional thawing such as short thawing time, easy process control, high-energy conversion, and the absence of water usage and generation of waste water (Roberts et al., 1998).

There are limited studies on Ohmic thawing and tempering of frozen foods in literature. This chapter gives information about the advantages and limitations of Ohmic thawing, and the factors affecting Ohmic thawing. In addition, the studies related to Ohmic thawing or tempering of frozen foods are briefly summarized.

23.2 THAWING AND TEMPERING

Thawing is usually defined as the reverse process of freezing, but it occurs slower than freezing because of the different physical properties of water and ice. Water has a higher heat capacity and lower thermal conductivity than ice, so, for an identical driving force, the thawing time will be longer than the freezing time (Delgado and Sun, 2001). Tempering is defined as increasing the temperature of frozen food to a higher temperature, but still below the initial freezing point (e.g., -5°C to -2°C). The product is still firm at this temperature, but can readily be further processed (James, 1999). Thawing is usually regarded as complete when the center of the food sample has reached 0°C . Lower temperatures (e.g., -5°C to -2°C) are acceptable for food that is destined for further processing, but such process is called tempering rather than thawing (James and James, 2002).

During thawing, foods are subjected to damage by chemical, physical, and microbiological changes. Fast thawing at low temperatures to avoid remarkable rise in temperature and excessive dehydration of food is desirable so as to assure food quality (Li and Sun, 2002). The most common thawing method is to apply heat to the surface of the frozen food by using air and to allow the heat to be conducted to the interior (Figure 23.1). The surface of the frozen food thaws first, but since the thermal conductivity of frozen foods is almost three times that of nonfrozen foods, the thawed surface has lower thermal conductivity than the frozen interior and cannot transfer adequate heat to the interior without increasing the temperature of the thawing surface to undesirable levels (Schaefer, 1999). Another common way of thawing is using cold water. This method is faster than using air, since heat-transfer coefficient of water is higher than air. However, water must be frequently changed to keep the temperature cold and to minimize microbial growth, which means a significant amount of water that must be treated as wastewater after use (Anderson and Singh, 2006). The disadvantages of conventional thawing methods are long thawing times resulting in changes in product quality and increased risk of chemical and biological deterioration of the food product, large space requirements, wastewater production, and loss of quality. With the increasing use of frozen foods, there is a greater need for improved thawing methods. Volumetric heating methods offer solutions to thawing problems. Volumetric heating does not require large amounts of water, and it is more rapid since the thermal conductivity of the food product does not control the thawing rate (Clements, 2006). Ohmic heating is one of the volumetric heating methods.

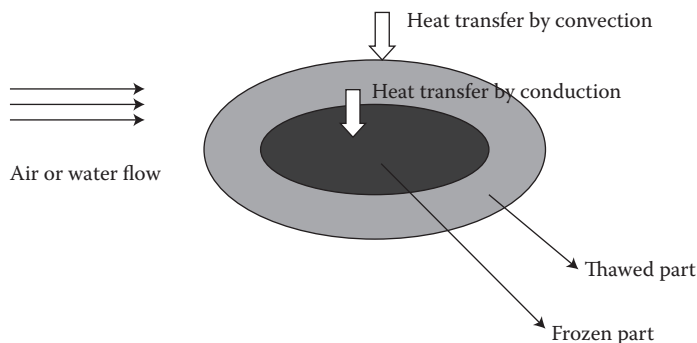


FIGURE 23.1 Conventional thawing mechanism of frozen foods by using air or water.

23.3 PRINCIPLES OF OHMIC HEATING

Ohmic heating (also known as Joule heating or electroconductive heating) provides a new heating method and a new inspecting technology for food processing. Ohmic heating is named after the Ohm's Law:

$$V = I \times R \quad (23.1)$$

where V is voltage (V), I is current (amp), and R is electrical resistance (ohm).

Ohmic heating is mainly based on the passage of alternating electrical current through a food product that serves as an electrical resistance (Reznick, 1996). Relatively rapid volumetric heating occurs due to the current passing through the food sample, and the temperature distribution is homogenous.

In practice, heating can be done by applying alternating current at low frequencies (50 or 60 Hz). Therefore, a power supply is simple and cheap. In addition, this low-frequency interval is the region in which the possibility of formation of electrochemical reactions is the lowest for the food materials (Tempest, 1995). But low frequencies have an electrolytic effect similar to that of direct current. The major outcome of the electrolytic effect is the dissolution of the metallic electrodes, which may contaminate the product (Reznick, 1996). To overcome this problem, high frequencies can be used in Ohmic heating applications.

The advantages of Ohmic heating are a shorter heating time, relatively low capital cost, easy process control, relatively uniform heating, and high-energy conversion efficiency. Ohmic heating has good energy efficiency since almost all of the electrical power supplied is transformed into heat and it has no limitation of penetration depth. The major disadvantage, on the other hand, is that Ohmic heating requires electrodes to be in good contact with the food. The food may also be immersed in a conducting liquid, like a weak salt solution of similar conductivity to the food. In that case, it is not necessary for electrodes to be in good contact with the food product.

Many factors affect the heating rate of foods undergoing Ohmic heating such as electrical conductivity and specific heat of the food, the product formulation, particle size, shape, and concentration (Kim et al., 1996).

23.4 OHMIC THAWING AND TEMPERING

Using Ohmic heating to thaw frozen foods is an innovative method. Ohmic thawing uses the electrical resistance of a frozen food product to generate heat volumetrically within the food product itself, as an electrical current is passed through the food product (Clements, 2006). Ohtsuki (1991, 1993) patented an Ohmic thawing process where frozen foods positioned with negative electrons were introduced into a high-voltage electrostatic field. Basically, the Ohmic thawing system is composed of a frozen food sample sandwiched between two electrodes that are connected to the Ohmic heating system (Figures 23.2 and 23.3). The critical point in Ohmic thawing is that the electrodes need to be in good contact with the frozen food. Otherwise, nonuniform heating and hot spots in the frozen food may be observed.

There are limited studies on Ohmic thawing and tempering (Naveh et al., 1983; Henderson, 1993; Roberts et al., 1998; Hong et al., 2007; Miao et al., 2007; Icier et al., 2010; Bozkurt and Icier, 2012; Seyhun et al., in press). Naveh et al. (1983) immersed the frozen product in an aqueous solution and used electroconductive heating to thaw the frozen sample positioned between two electrodes having no direct contact with the sample. The researchers concluded that electroconductive thawing was a rapid thawing method since they found that 160 min was enough to thaw the meat sample completely by using electroconductive method, whereas 450 min was required to thaw the same frozen food sample in a 20°C stirred water bath. They also claimed that the fast thawing rate in electroconductive heating is independent of medium temperature; therefore, the thawing process

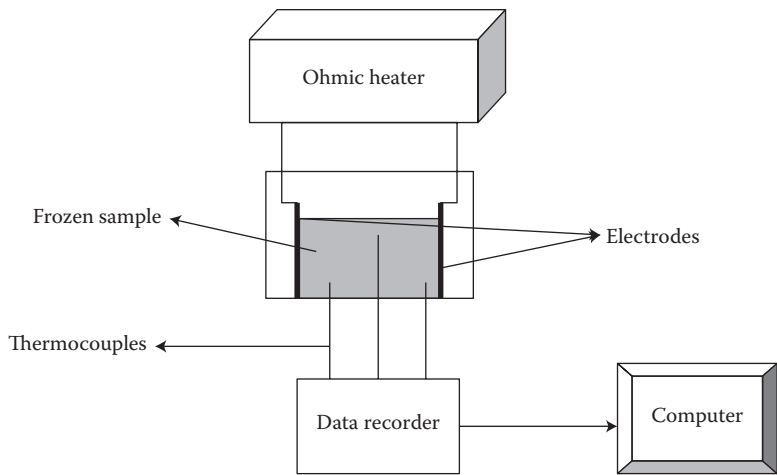


FIGURE 23.2 General scheme of Ohmic thawing setup.

can be conducted with a low product surface temperature, which is very important for preventing microbial growth during thawing.

Henderson (1993) used Ohmic heating to thaw shrimp blocks and found that as the frozen product thawed, current passes through the thawed portion of the block more readily, following a path of least resistance.

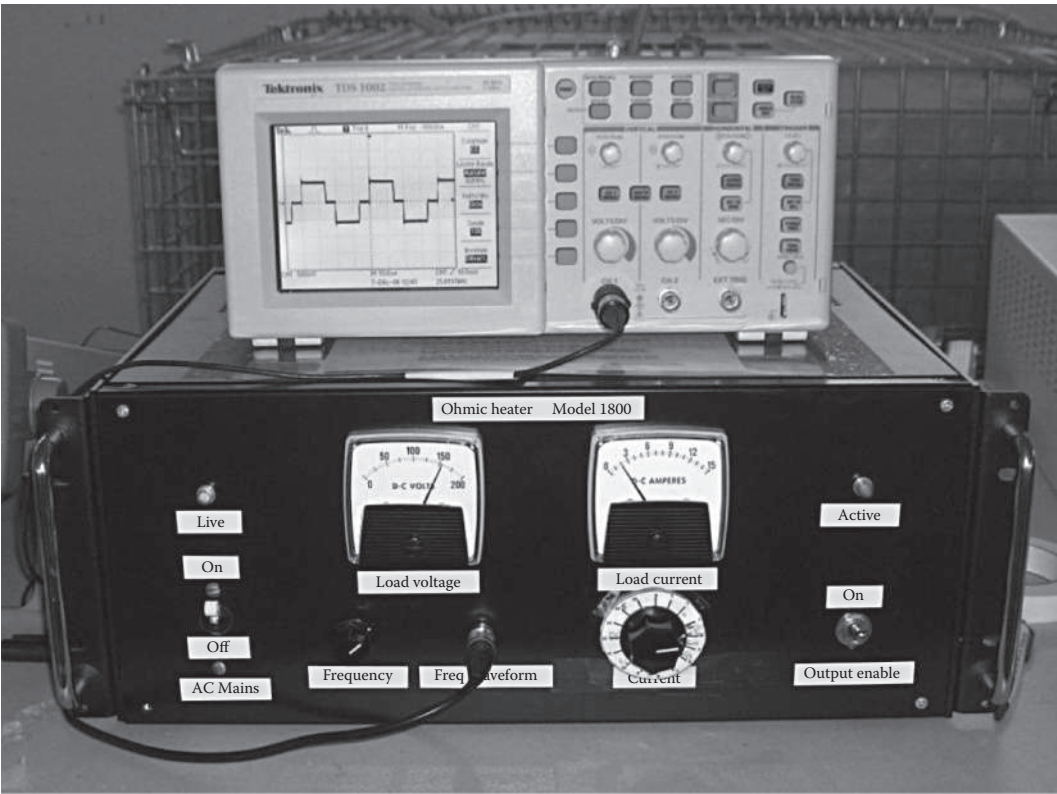


FIGURE 23.3 Ohmic heater.

Roberts et al. (1998) designed and tested an automated, computer-controlled prototype Ohmic thawing unit, and the performance of this unit was tested with frozen shrimp blocks. The sample chosen was frozen shrimps on purpose, since 70% of shrimp processed in Florida is imported in the form of rectangular frozen blocks and these frozen shrimp blocks need to be thawed before further processing and handling. Mostly warm water was used to thaw these blocks since water had a high heat-transfer coefficient and using water reduced moisture loss in shrimps during thawing, but the thawing process was slow and the product was subjected to microbial growth due to higher surface temperatures. They concluded that it was not necessary to use water for Ohmic thawing, therefore the thawing procedure did not generate much wastewater, and it was more energy efficient. Moreover, the test results proved that the time for Ohmic thawing was comparable to time for water immersion thawing, without the incidence of hot spots.

Hong et al. (2007) investigated the effects of Ohmic thawing on physicochemical properties of frozen pork muscle and found that more rapid thawing rate was seen with the electrode contacts thawing system than with brine immersion thawing. In terms of physicochemical properties, brine immersion thawing can be preferred at high-voltage levels while lower voltage levels can be used for electrode contact thawing system.

Miao et al. (2007) studied Ohmic thawing of frozen surimi by infusing an electrode solution into the sample container so that the frozen surimi sample was electrically connected with the two electrodes. They used a chamber held at 0°C as the conventional thawing method. A homogeneous temperature distribution in the frozen surimi was obtained when the concentration of electrode solution was below 4.0%.

Icier et al. (2010) compared the histological and textural changes of beef cuts during Ohmic thawing and conventional thawing, and they found that the changes in the histology and the texture of the thawed meat sample were lower than conventionally thawed ones. Further, Bozkurt and Icier (2012) carried out an extensive study on Ohmic thawing of frozen beef cuts, and they inspected the effects of sample size and voltage gradient on thawing time, drip loss, color, temperature homogeneity, and energy utilization ratio. The results showed that all samples were thawed successfully by Ohmic thawing, and Ohmic thawing significantly decreased thawing time and thawing loss while increasing the temperature homogeneity. The minimum temperature homogeneity was calculated as 0.90 in Ohmic thawing, whereas the values obtained in conventional thawing ranged between 0.56 and 0.61 (depending on the sample size).

Seyhun et al. (in press) used high frequency (10–30 kHz) Ohmic heating for tempering frozen potato puree samples. They investigated the effects of different frequency levels and different salt concentrations on electrical conductivity and tempering time.

23.4.1 ADVANTAGES OF OHMIC THAWING AND TEMPERING

Long processing times in conventional thawing increases risk of chemical and biological deterioration of product. The advantages of Ohmic thawing are shorter thawing time, high heating rate, easy process control, no water used in the process and no wastewater generated, and high-energy conversion efficiency (Roberts et al., 1998). Using this method, frozen foods can be thawed rapidly in the temperature range of –3 to 3°C. For instance, the thawing time for frozen tuna, beef, and eggs was shortened to 1/4–1/3 of that of conventional thawing under the same temperature condition (Li and Sun, 2002). Yun et al. (1998) examined Ohmic thawing of frozen chunks of meat in combination with conventional water immersion thawing, and they found that Ohmically thawed samples showed reduced drip loss and improved water-holding capacity when lower voltages were applied.

Roberts et al. (2002) compared quality attributes of Ohmic and water immersion thawed shrimp and found that there were no significant differences in sensory quality and the microbial load between thawing methods. Ohmic thawing was stated to have environmental and economical advantages over water immersion thawing.

TABLE 23.1
Comparison of Tempering Times (s) for Ohmic Heating

Frequency (kHz)	Salt Concentration (%)		
	1.00	0.75	0.50
10	250	300	430
20	240	290	400
30	210	260	330

Source: With kind permission from Springer Science+Business Media: *Food and Bioprocess Technology*, Ohmic tempering of frozen potato puree, DOI: 10.1007/s11947-012-1002-7, in press, Seyhun, N. et al.

Seyhun et al. (in press) compared the Ohmic tempering times of frozen potato puree with conventionally tempered frozen potato puree. The frozen potato puree samples were tempered conventionally by natural convection at 4°C, and it took almost 50 min to temper the frozen potato puree samples, whereas Ohmic tempering time with Ohmic heating took 3.5–7.2 min depending on the chosen salt concentration and frequency of the electrical current (Table 23.1). There was a significant decrease of tempering time with Ohmic heating technique.

Miao et al. (2007) also compared Ohmic thawing and conventional thawing at 0°C of frozen surimi, and they found that the thawing time was considerably reduced to 59 min by Ohmic heating with a 2% electrode solution when compared to a thawing time of 580 min by conventional thawing.

23.4.2 TECHNICAL CONSIDERATIONS

The Ohmic thawing setup is technically simple (Figure 23.2), but performance of this method depends on the good contact between the electrodes and product. There would be no problem with a rectangular-shaped product, but spherical or oddly shaped products may present a problem in achieving such a good contact. The shape limitation is the most important drawback to use Ohmic thawing technology in food industry. To overcome this problem, an electrode solution can be used, by this method there is no direct contact between the electrodes and the frozen food product. This method was first proposed by Naveh et al. (1983), and also used by Miao et al. (2007) to thaw frozen surimi.

Another disadvantage of Ohmic thawing may be the hot spots observed during thawing of frozen foods. Electrical conductivity of frozen food is twice lower than that of thawed food. Thus, thawed portion of a food can be cooked while the rest of the food can be still frozen (Goullieux and Pain, 2005).

Seyhun (2008) attempted to thaw frozen food samples (at –25°C) by Ohmic heating, but no current was observed at that temperature level, meaning that Ohmic heating was not effective. To understand the reason of this problem, a set of experiments were performed with water including very high concentrations of salt like 10%, 20%, 30%, and these salt solutions were chilled. Since addition of salt decreased the freezing point of the salt solutions, the solutions that were not frozen but chilled (still in liquid state) were heated very fast by Ohmic heating. Thus, it was concluded that the physical state of the food sample was also very important for Ohmic heating studies, since it was harder to conduct electricity in solid bodies.

23.4.3 FACTORS AFFECTING OHMIC THAWING AND TEMPERING RATE

The most important food property while applying Ohmic heating is the electrical resistance or the electrical conductivity of the food product. In general, solids exhibit significantly lower electrical conductivities than liquids. When the foods are frozen, they change their physical state from

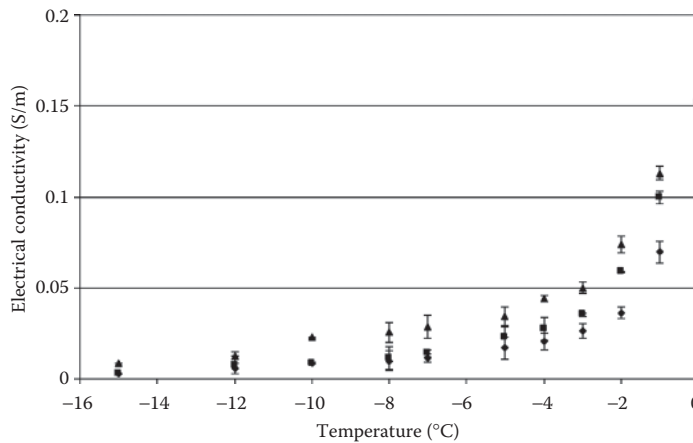


FIGURE 23.4 Effect of salt concentration (◆, 0.50%; ■, 0.75%; ▲, 1.00%) on electrical conductivity of frozen potato puree at 30 kHz. (With kind permission from Springer Science+Business Media: *Food and Bioprocess Technology*, Ohmic tempering of frozen potato puree, DOI: 10.1007/s11947-012-1002-7, in press, Seyhun, N. et al.)

liquid-to-solid form, resulting in lower electrical conductivity values due to decreased ionic mobility. Electrical conductivity depends mainly on temperature. As the temperature of the frozen food product increases, the electrical conductivity increases substantially with temperature (Palaniappan and Sastry, 1991). Electrical current flow increases with increasing temperature, and according to Ohm's law the resistance of the sample decreases, meaning an increase in electrical conductivity. Therefore, the factors affecting the electrical conductivity like temperature, frequency, and salt concentration of the food sample or the aqueous solution also affect the Ohmic thawing rate. The electrical conductivity increases with increasing salt concentration (Figure 23.4), and the effect is pronounced more at relatively higher temperatures. Since the electrical conductivity increases, the Ohmic thawing rate increases with increasing salt concentration as well. Likewise, increasing frequency increases the electrical conductivity values of frozen food products (Figure 23.5).

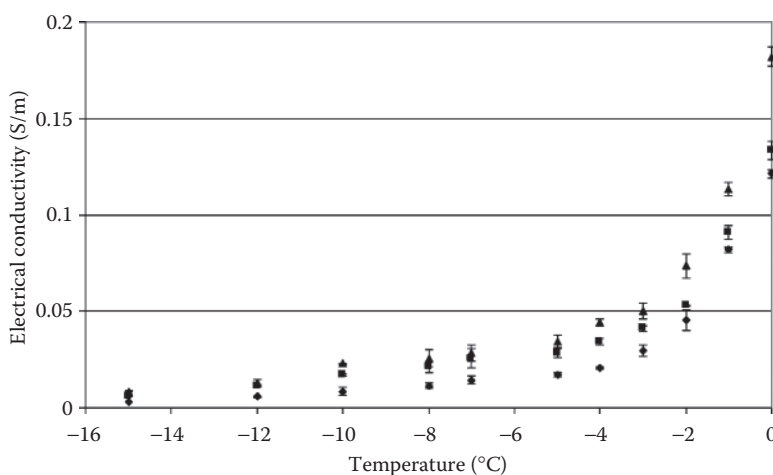


FIGURE 23.5 Effect of frequency (◆, 10 kHz; ■, 20 kHz; ▲, 30 kHz) on electrical conductivity of frozen potato puree with 1.00% salt concentration. (With kind permission from Springer Science+Business Media: *Food and Bioprocess Technology*, Ohmic tempering of frozen potato puree, DOI: 10.1007/s11947-012-1002-7, in press, Seyhun, N. et al.)

23.4.3.1 Salt Concentration

As mentioned above, salt concentration of the frozen foods is an important parameter in Ohmic thawing studies since the electrical conductivity of the foods decreases by reducing salt concentration (Figure 23.4). Applying Ohmic heating is dependent on the product's electrical conductivity, since the amount of heat generated in Ohmic heating is directly related to the current induced by the voltage gradient in the field, and the electrical conductivity of the material being heated (Sastry and Li, 1996). Thus, the electrical conductivity of food materials is a critical parameter, and the increase of the electrolytic content within foods, which causes high electrical conductivity, can be achieved by salt addition.

Increasing the salt concentration is an effective way of improving the Ohmic thawing effectiveness, but salt concentrations higher than 1% are not preferable for food industries, so salt concentrations have to be chosen considering the industrial criteria. If the salt concentration is very low, it is possible not to observe any current at low temperatures during thawing, which decreases the effectiveness of the Ohmic thawing process.

Seyhun et al. (in press) investigated the effect of salt concentration on the temperature profile of frozen potato puree. As the salt concentration of the frozen potato puree sample decreased, the tempering time increased (Figure 23.6). This is because the electrical conductivity of the frozen potato puree decreased by the reduction of salt concentration (Figure 23.4). The salt concentration was also shown to affect the uniformity of temperature distribution. As the salt concentration decreased, the temperature distribution was observed to be more uniform (Seyhun et al., in press).

If the frozen product is immersed in an electrode solution for Ohmic thawing, then the salt concentration of the electrode solution becomes a critical parameter. Miao et al. (2007) showed that the thawing rate of frozen surimi with Ohmic heating increases linearly with the increasing concentration of the electrode solution, with a concentration range of 0.1–0.8%.

23.4.3.2 Frequency

The Ohmic thawing rate is strongly dependent on the frequency of the electrical current. Seyhun et al. (in press) showed that the tempering time of the frozen samples decreased as the frequency

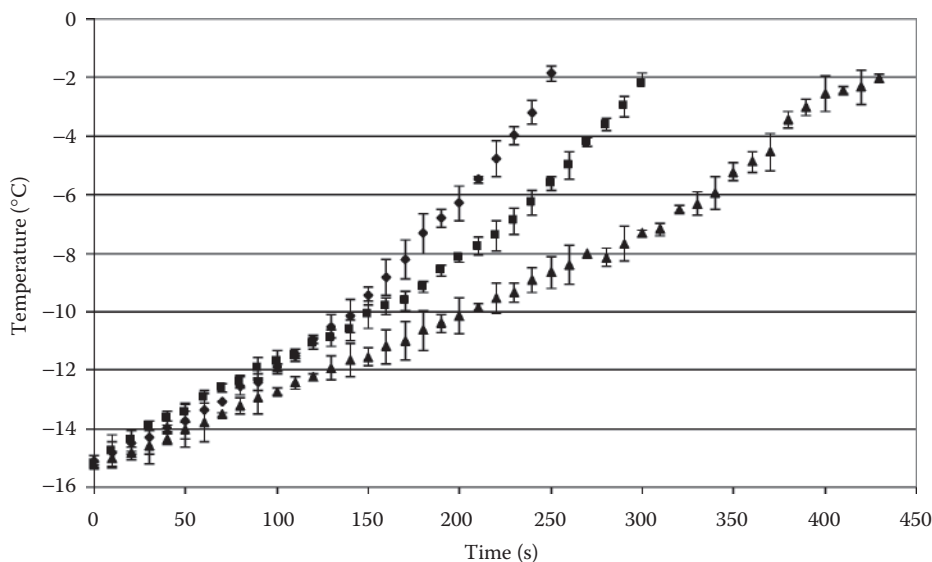


FIGURE 23.6 Effect of salt concentration (◆, 0.50%; ■, 0.75%; ▲, 1.00%) on surface temperature profile of Ohmic tempering at 10 kHz. (With kind permission from Springer Science+Business Media: *Food and Bioprocess Technology*, Ohmic tempering of frozen potato puree, DOI: 10.1007/s11947-012-1002-7, in press, Seyhun, N. et al.)

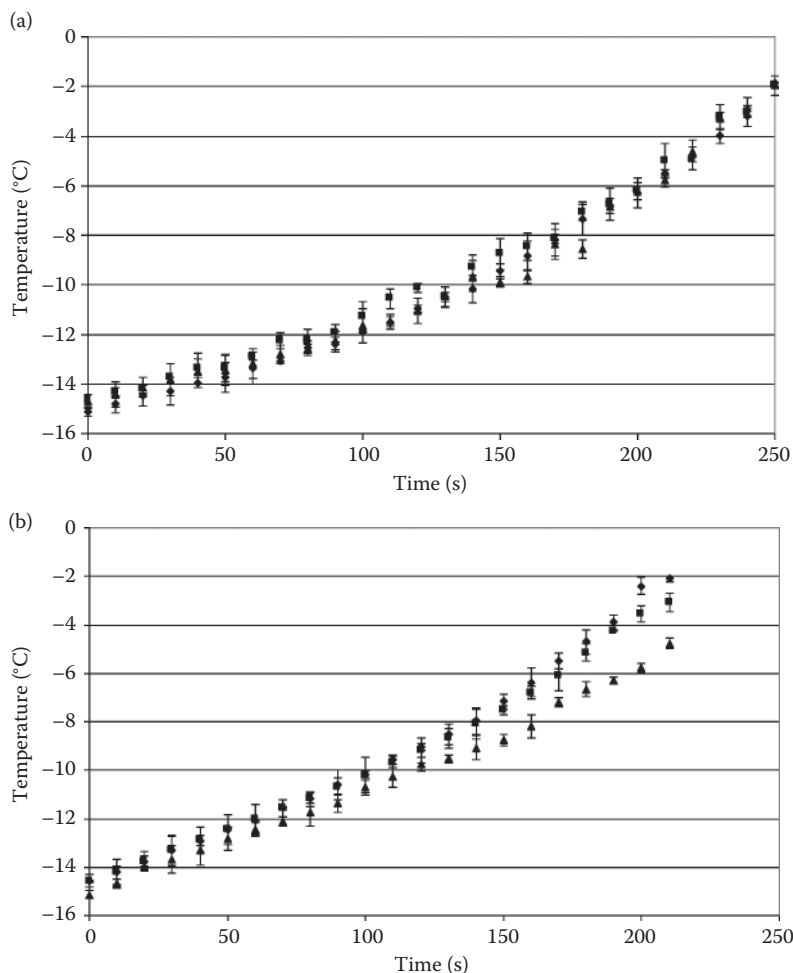


FIGURE 23.7 Temperature profile of frozen potato puree with 1.00% salt during Ohmic tempering (a) at 10 kHz (b) 30 kHz (◆, surface; ■, middle; ▲, center). (With kind permission from Springer Science+Business Media: *Food and Bioprocess Technology*, Ohmic tempering of frozen potato puree, DOI: 10.1007/s11947-012-1002-7, in press, Seyhun, N. et al.)

increased (Table 23.1). This is because the electrical conductivity also increases by increasing frequency (Figure 23.5) and as a consequence the tempering time decreases.

The temperature distribution inside the frozen foods during Ohmic thawing is an important criterion since uniform temperature distribution is desired for thawing processes. Seyhun et al. (in press) investigated if the temperature distribution inside the frozen potato puree samples is uniform at different frequencies (10, 20, 30 kHz) and salt concentration levels. At 10 kHz, the temperature distribution is found to be more homogeneous inside the frozen potato puree sample at the same salt concentration, since the tempering time was longer and this allowed longer conduction resulting in a more homogenous temperature distribution (Figure 23.7).

23.4.3.3 Voltage Gradient

Some Ohmic thawing applications are performed at a constant frequency, but using different voltage gradients. Bozkurt and Icier (2012) found that Ohmic thawing rate was not affected up to the initial freezing temperature of the food, but it increased significantly after that point. Eventually, the

thawing time decreased with increasing voltage gradient. However, increasing voltage ingredient may not be very effective for tempering purposes since the temperature of the frozen foods rises to just below their freezing point in tempering.

23.4.3.4 Sample Size

The size of the food sample is a significant factor on the Ohmic thawing rate and temperature homogeneity throughout the food. The thawing time increases as the size of the sample increases. Bozkurt and Icier (2012) showed that Ohmic thawing rate decreased significantly with increasing sample size above the freezing temperature, whereas there was no significant difference below that temperature. The researchers also found that the temperature homogeneity decreased with the increased sample size (Bozkurt and Icier, 2012).

23.5 CONCLUSIONS

Ohmic thawing is a novel thawing technology, and the most important advantage of Ohmic thawing is to shorten the thawing time significantly. The shorter the thawing time, the lesser the microbial growth, and the better is the final quality of the thawed product. But Ohmic heating have limitations when applied for thawing and tempering purposes. The solid state of frozen samples, the need of good contact of the sample with the electrodes, and the electrical conductivity of the sample complicate the Ohmic thawing and tempering process. The size, the shape, and the electrical conductivity of the frozen product should be carefully optimized to obtain higher efficiencies.

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24 Ohmic Heating as an Aseptic Sterilization Process for Particulate Foods

Luc Fillaudeau and Legrand Alexandra

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24.1 INTRODUCTION

Owing to industrial and social requirements, but also due to technical and scientific progress, the food processing industry is facing new challenges: a wide diversification of processing equipment and the emergence of new food matrices that are more complex. Meanwhile, the choice of technologies and processes should achieve the following goals: (i) to ensure the microbiological security of a given product up to a date limit; (ii) to improve product quality through a better control and understanding of the process, and (iii) to enhance the competitiveness and reliability of the process.

Commercial food products, such as prepared dishes, are mostly solid–liquid mixtures. The traditional technique used by the food industry to sterilize these products is canning. However, continuous processing of heterogeneous liquid–particle food products with conventional or alternative technologies (e.g., Ohmic heating) is being increasingly advocated as a substitute for batch sterilization. In continuous processes, the product flows continuously throughout the heating, holding, and cooling sections. Packaging should be realized under controlled atmosphere and aseptic conditions in agreement with product shelf life and safety. The expected advantages of a continuous process are an increase in production capacity, a reduction in power consumption, an improved treatment homogeneity and less damage to the particles. However, the passage from a batch to a continuous

processing in order to achieve a high-temperature short-time (HTST) treatment of solid–liquid mixtures is challenging and mostly it is an empirical challenge. Numerous criteria should be considered in relation with food science and food processing (Figure 24.1). Ohmic heating is a promising way for aseptically processing fluids containing large particles (i.e., equivalent diameter ranging from 1 to 30 mm). With this process, solids can often heat faster than liquids, a result impossible to achieve using other heating techniques. The other advantages include uniform heating, high solid capacity (can process up to 80% solids and 20% vol/vol liquids), reduced fouling and particle

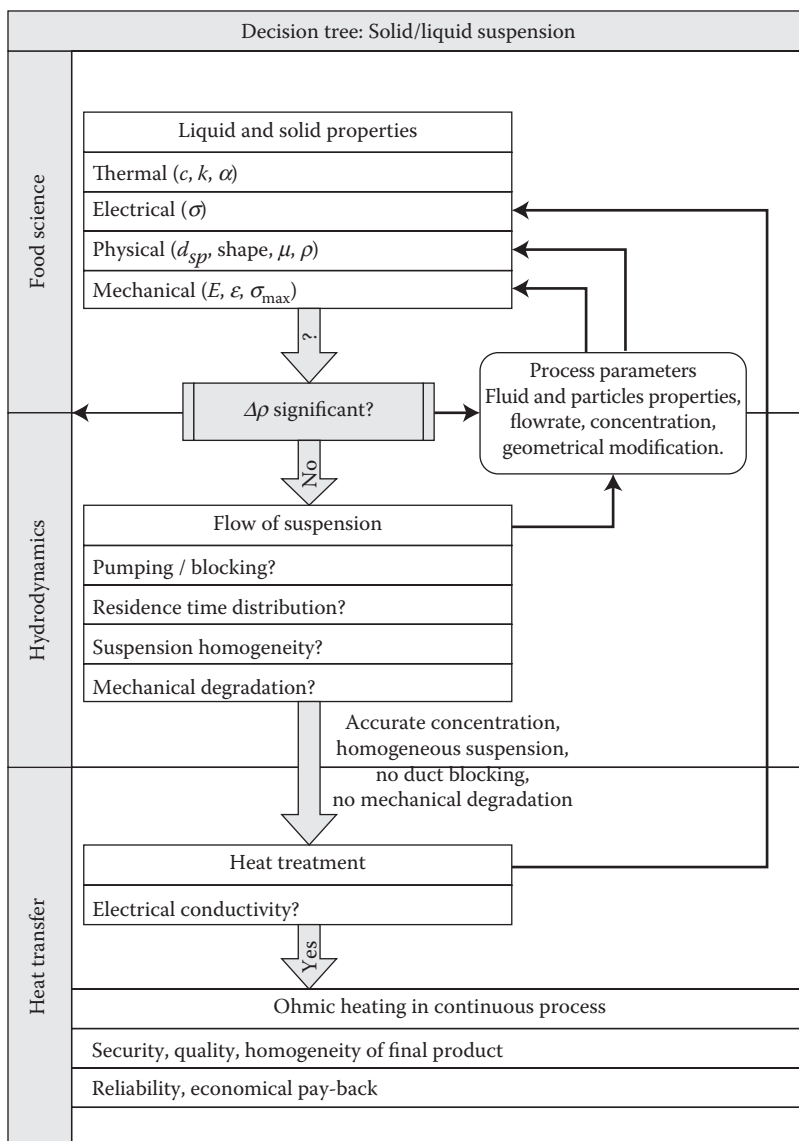


FIGURE 24.1 Scientific locks and critical factors for passage from a batch to continuous Ohmic heating process for complex solid–liquid food suspension—decision tree. (From IFT 2006—Annual Meeting June 24–28, Fillaudeau, L., Ohmic heating of complex foods in continuous process—Challenges and solutions, Copyright 2006a; *Journal of Food Engineering*, 81, Legrand, L. et al., 447–458, Physical, mechanical and thermal and electrical properties of cooked red bean (*Phaseolus vulgaris* L.) for continuous Ohmic heating process, Copyright 2007a, with permission from Elsevier.)

damage and faster start-up and shut-down to produce a better quality product than conventional heat exchangers (Zoltai and Swearingen, 1996; Yang et al., 1997; Zuber, 1999; Leizerson and Shimoni, 2004; Zuber et al., 2000). Overall, the three main factors to consider in process design are (i) particles and liquid flows, (ii) heat transfer and (iii) quality optimization.

First, the continuous processing should enable produce, a constant flow of a homogeneous suspension without blocking or mechanically degrading the (fragile) particles, while operating over a range of concentrations or electrical conductivities (Ohmic heating). Literature data (Chandarana, 1992; Singh and Lee, 1992; Sastry, 1993; Abdelrahim et al., 1993) indicate that, the major factors influencing particle velocity in a stream of carrier fluids are: viscosity, relative density (particle to fluid), relative size (particle to tube), particle shape, and concentration of the solid phase in the fluid. Therefore, it is essential to have a perfect knowledge of the physical, mechanical, thermal, and electrical properties of the particles and the carrier fluid to develop continuous thermal processing. From scientific and industrial standpoints, the knowledge and the control of the product's properties lead to the identification of several limiting factors (maximal concentration and mechanical degradation of particles, duct plugging, heterogeneity of the suspension flow or electrical conductivity, heterogeneity in generated heat and heat transfer, widespread of sterilization or cooking efficiencies) in relation with the process or heating technologies. Industrial users often find that the published physical property data are unsuitable for industrial use because most materials are inhomogeneous and have a complex structure, and model systems tend to omit many of the minor ingredients in commercial formulations. Moisture and air content ranges tend to cover only a relatively narrow band, unrepresentative of real systems and data for both elevated temperatures and low temperatures are sparse.

Second, microbial safety and nutritional quality of liquid–solid mixtures being functions of time and temperature in the aseptic processing system; consequently, residence time distribution (RTD) and heat transfer (between wall and suspension, and between particle and fluid) studies have been carried out by many authors (Dutta and Sastry, 1990a,b; Chandarana, 1992; Sastry, 1992, 1993; Zaboubi, 1995; Palmieri et al., 1992; Aström and Bark, 1994; Fairhurst and Pain, 1999; Eliot-Godereaux et al., 2001a,b) using real food particles such as carrots or potato cubes or model particles, which were often made of alginate. In a continuous process, hydraulic and thermal phenomena, that is, suspension flow (Sastry and Zuritz, 1987; Lareo and Fryer, 1998) and heat transfer surrounding the particles (Baptista et al., 1997a,b; Barigou et al., 1998) are closely associated. Although Ohmic heating stands as a smart way to heat solid–liquid suspensions and liquid foods with specific advantages due to the technology; Ohmic heating could not be considered as a “Plug-and-Play” technology. Several critical factors should be identified and controlled, for example, a steep temperature gradient between fluid and electrode, the occurrence of mixed convection, the growth of fouling deposit at electrode surface, the stability of thermal and electrical parameters, the homogeneity of suspension and integration of knowledge and know-how in food science and food processing (Fillaudeau, 2007; Ghnimi et al., 2009a,b).

In this chapter, the continuous heat treatment of solid–liquid food suspensions using direct Joule effect technology is described in relation with particle properties, flow and heat-transfer criteria. The limited factors for a transition from a batch to a continuous process and the beneficial aspects are reported and illustrated.

24.2 PARTICLES PROPERTIES: IMPACT AND LIMITATIONS

Food properties constitute the first data that must be known and controlled to investigate the continuous processing of solid–liquid suspensions with conventional or Ohmic heaters (Figure 24.1—Food science). Overall properties such as physical (density, shape and dimension, rheology), mechanical (elasticity modulus, maximal deformation, and stress), thermal (heat capacity, thermal conductivity, thermal diffusivity), and electrical (electrical conductivity) properties of fragile particles and carrier fluid help to establish several recommendations and to identify the related limiting factors for transition from a batch to a continuous Ohmic heating process.

Physical properties include density, particle size distribution, and the rheological behavior of the carrier fluid. In a continuous process, the relative density (particle to fluid) appears to be essential to characterize the heterogeneity of a flowing suspension (decantation, flotation). Density differences between solids and fluid, although slight, may be sufficient to generate particle settling (Liu et al., 1993) and consequently different sterilization and cooking efficiencies between solid and liquid phases and among the solid phases. The particle size is a factor affecting the quality of processed dishes (Grabowski and Ramaswamy, 1995). The length, thickness, and width of particles are generally measured using a sliding caliper. However, they could be measured much faster and more accurately using other methods, such as the Machine Vision System or image analysis. Apparent viscosity is a fundamental parameter, not only as a time–temperature integrator (TTI) of final product quality, but also for following intermediate processes for sizing heat exchanger equipment and for estimating mechanical stress. The rheological properties must be known for fluid mechanic studies in order to characterize nature of the flow (Holdsworth, 1971). Determining the flow regime specification (laminar, transition, or turbulent) requires the calculation of the Reynolds number. Today, much data has been published on the rheological behavior of Newtonian and non-Newtonian fluids. In contrast, not much is available on the rheological behavior of suspensions, particularly when the carrier fluid is non-Newtonian (Bhamidipati and Singh, 1990).

Mechanical properties play an important role in measuring the cooking quality and the magnitude of particle damage along the process. Numerous methods have been developed to determine the texture, but data are frequently incomparable between laboratories due to the lack of standardization. The incidence of heat treatment on the texture has been studied for various vegetables (Rao et al., 1981; Leung et al., 1983; Van Loggerenberg, 2004; Van der Merwe et al., 2006; Legrand et al., 2007a,b). The mechanical properties are significantly affected by the mode of cooking (Cheng and Sun, 2004). For a lot of fruits and vegetables, the force required to cause a given deformation decreases as the temperature, heating and hydration times increase (Abu-Ghannam, 1998). Different correlations between the parameters obtained (elasticity, hardness), the cooking time (Singh et al., 2005), the physical and chemical properties and the time passage (Nourian et al., 2003) were established.

Thermal properties (specific heat capacity, thermal conductivity, thermal diffusivity) aid in sizing the thermal equipment and understanding the food transformation; for example, the evolution of the Biot number along the process affects the heating kinetics inside the particle. Specific heat capacity can be determined using the knowledge of each component in the mixture. Modeling the thermal conductivity is much more difficult because, it involves the structure (e.g., porosity, anisotropy). The last three decades have seen much effort and progress in developing measurement techniques to obtain new data on the thermal properties of foodstuffs (Ali et al., 2002; Mayer, 2003; Nesvadba et al., 2004; Pakkala et al., 2006).

The electrical conductivity of the suspension constitutes a fundamental parameter in Ohmic heating. Several authors have reported the electrical conductivities of various liquid foods (Palaniappan and Sastry, 1991a; Sastry and Palaniappan, 1992; Fryer et al., 1993; Yongsawatdigul et al., 1995; El-Hajal, 1997; Marcotte et al., 1998; Davies et al., 1999; Li et al., 2004) and a global equation was proposed by Fillaudeau (2004). A set of electrical conductivity parameters was obtained for particles by many researchers (Mitchell and de Alwis, 1989; Halden et al., 1990; Palaniappan and Sastry, 1991b; Kim et al., 1996; Wang and Sastry, 1997; Marcotte, 1999; Shirsat et al., 2004). Generally, solid vegetable particles have lower electrical conductivities than liquids but, many factors affect the electrical conductivity: electrolyte concentration (Wang and Sastry, 1993), particle orientation and shape (de Alwis et al., 1989), particle concentration (Zareifard et al., 2003), food composition changes and heating effects (Halden et al., 1990), the specific heat (Zoltai and Swearingen, 1996), the viscosity (Khalaf and Sastry, 1996), the temperature (Wang and Sastry, 1997; Marcotte et al., 1998), the liquid/solid electrical conductivity ratio (Sastry and Palaniappan, 1992). Several authors have proposed many different correlations according to these experimental parameters (Palaniappan and Sastry, 1991b; Fryer et al., 1993; Yongsawatdigul et al., 1995) but never proposed a single relationship for all the products. Finally, although a large amount of data has been published

on Ohmic heating of homogeneous suspensions, not much is available on the electrical conductivity of heterogeneous liquid products containing large particles. Generally, the size and the shape of the particle are the same (sphere, cylinder) and experiments using real food products as in canned food are insufficient or irrelevant.

24.2.1 LIMITING FACTORS CORRELATED TO PHYSICAL PROPERTIES

Real and nonuniform particles (i.e., vegetables) are subjected to a wide dispersion. The mean values of the particle dimensions (length, width, and thickness) associated to their standard deviations are reported in literature and they have been shown to follow a normal distribution with a relatively high standard deviation. Ogunjimi et al. (2002) reported that particles could be classified into three categories namely small, medium, and large within a defined population. In Legrand et al. (2007a,b), particles were classified as large, based on their length or equivalent sphere diameter, d_{sp} . As expected, the significant amount of absorbed water involved an increase of particle size, and volume and particle dimensions could be described versus the moisture content by empirical models (Figure 24.2). For example, Legrand et al. (2007a,b) report that red beans (*Phaseolus vulgaris* L.) are large particles with an equivalent diameter of the same order of magnitude as the pipe ($d_{sp}/\phi > 0.10$): irregular shape, with a wide range of surface areas and mechanical properties depending on their moisture content and their natural dispersion. In continuous processes, an increase of particle dimension limits the maximal particle concentration at the inlet due to a volume expansion along the process. Legrand et al. (2007a,b) analyzed the flow behavior of the same product and defined quantitative criteria to describe the suspension. Suspension heterogeneity and the flow pattern depend on four major parameters: the orientation of the tubes and the density differences (and associated dispersion) between the carrier fluid and the particles; but the shape and the mechanical properties of particles are factors which limit particle concentration increase and cause fluids to tend toward homogeneity. The rheological behavior of the carrier fluid affects the particle residence time and high viscosities afford some degree of protection to the particle, but also influence the velocity profiles in the continuous system. Knowing the distribution of both liquid and particle velocities is essential for a sound process design.

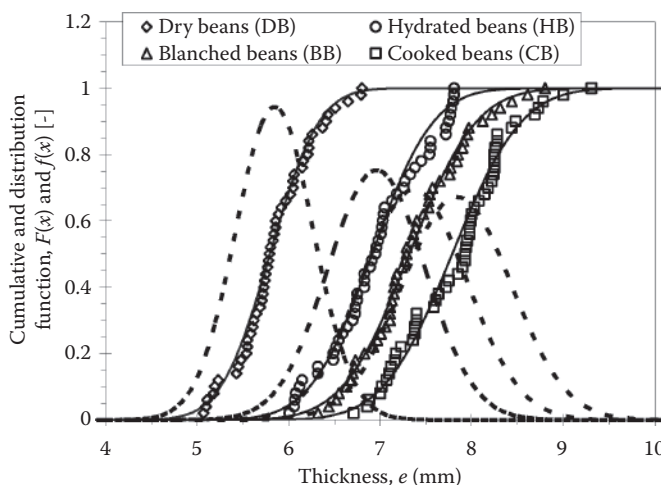


FIGURE 24.2 Normal distribution of particle thickness (red bean, *Phaseolus vulgaris*)-versus water content along sterilization process (absolute water content: $n_{DB} = 0.15$, $n_{HB} = 1.14$, $n_{BB} = 1.64$ and $n_{CB} = 2.07$ gH₂O/gDM). (From *Journal of Food Engineering*, 81, Legrand, L. et al., 447–458, Physical, mechanical, thermal and electrical properties of cooked red bean (*Phaseolus vulgaris* L.) for continuous Ohmic heating process, Copyright 2007a, with permission from Elsevier.)

24.2.2 LIMITING FACTORS CORRELATED TO MECHANICAL PROPERTIES

The mechanical properties (elastic modulus, maximal stress, and deformation) are measured in one dimension (thickness), whereas fragile particles (vegetables, seeds, meats) exhibit a strong anisotropy in mechanical properties. In fragile particles, the compressive force increased with an increase in deformation. There was a sharp decrease in the force after particle rupture. The force required for causing a given deformation decreased as the moisture content increased, as reported by Abu-Ghannam (1998). This may be due to the fact that at higher moisture contents, the particles became softer and required less force to break them. The particles are assumed to exhibit elastic behavior, obeying Hooke's law. Young's modulus is properly determined from the initial section of the stress-strain curve, at relatively low deformation (Shitanda et al., 2002).

The shape and mechanical properties of the particles are limiting factors in increasing their concentration (maximal volume fractions). Indeed, mechanical properties define the ability of particles to flow through a pipe with mechanical inter-particle and particle-wall interactions. Fragile particles tend to break due to the presence of the many bends and obstacles (enlargements, reductions) in the continuous process. An insufficient mechanical resistance leads to a severe reduction in particle size generally involving blockage of the pilot plant (Legrand, 2005). In order to keep the particle whole, a low solid concentration is required but this could be far from economic reality. Particle dimensions, and hence volume increase along the process and this should be taken into account in determining the maximum packing volume fraction in continuous heat treatment, in order to avoid duct blocking and mechanical degradation. However, at a low solid concentration, the density differences observed between each phase can be sufficient to cause a severe suspension heterogeneity, which will naturally contribute to the mechanical damage of the particles. Decantation or flotation will generate first, the collisions with the wall and, second, the flow of two separate phases. During processing, fragile particles may lose their elasticity, E and become softer and rather prone to breaking, τ_{\max} (Figure 24.3) with increasing moisture content that tends to be incompatible with continuous heat treatment.

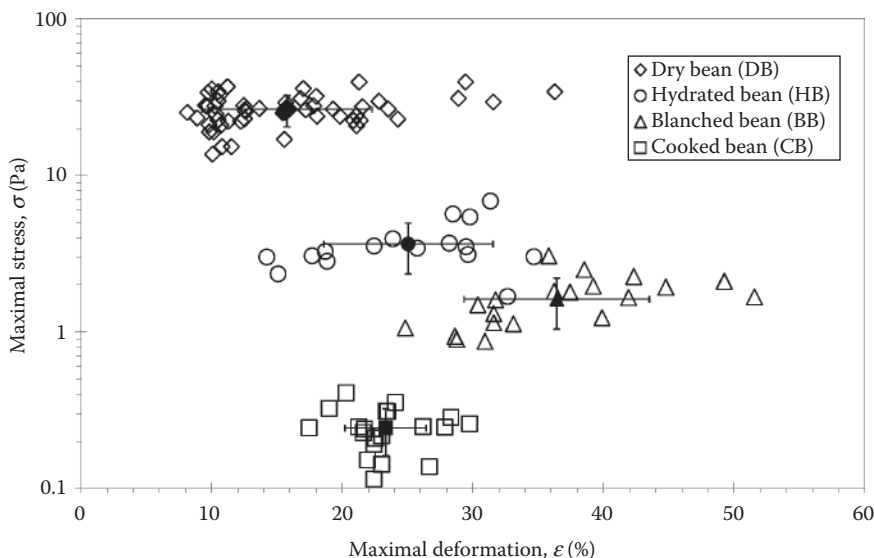


FIGURE 24.3 Maximal stress versus maximal deformation for particles hydration rate along the sterilization process (particle: red bean, *Phaseolus vulgaris* and absolute water content: $n_{DB} = 0.15$, $n_{HB} = 1.14$, $n_{BB} = 1.64$ and $n_{CB} = 2.07$ gH₂O/gDM). (From *Journal of Food Engineering*, 81, Legrand, L. et al., 447–458, Physical, mechanical, thermal and electrical properties of cooked red bean (*Phaseolus vulgaris* L.) for continuous Ohmic heating process, Copyright 2007a, with permission from Elsevier.)

24.2.3 LIMITING FACTORS CORRELATED TO THERMAL PROPERTIES

Sterilization of a suspension is more complex. Heterogeneity and settling suspensions have a simultaneous incidence on the flow of the suspension and on heat transfer (Legrand, 2005; Legrand et al., 2007a,b). Conventional thermal processing can be successful for single-phase fluids, but is limited in its applicability to multiphase foods. In this case, the time required to conduct heat to and from the centers of the particles during a process could be a limiting factor. Heat transfer from the surface to the center of the particle is defined by the Biot number, Bi , which characterizes the heterogeneity between the heating kinetics of the fluid and of the particles. Particle size and relative velocity intervene primarily on the heat-transfer coefficient between the fluid and the particle, h_{fp} and heat transfer is strongly influenced by the cross-sectional distribution of the solid phase in the pipe and the flow of each phase. In addition, the dimension and thermal conductivity of particles evolve along the process and affect the Biot number.

The sterilization efficiency concerning the particles and carrier fluid will be closely correlated to the flow behavior of the suspension, especially when particle density shows a wide dispersion, as in the case of real particles (high standard deviation). Hence, under such conditions a “fastest-particles process” design strategy would lead to over-processing of the majority of particles. This phenomenon may cause local overheating, when the moving bed pattern is considered, the heat transfer increases above the bed by the mixing effect of the particles. But when the cooking time is too high, particles become softer and lead to degradation of the solid tissue and consequent loss of product quality. In many cases, the extent of particle damage observed during the heat treatment would be unacceptable for a consumer product.

24.2.4 LIMITING FACTORS LINKED TO SUSPENSION PROPERTIES

In Ohmic heating, if the solid and liquid have identical electrical conductivities, both phases will generate heat at the same rate and the suspension will heat both rapidly and uniformly. Unfortunately, in practice, the problem is more complex, because the electrical conductivity of each phase (particle and surrounding fluid) is often significantly different and the mean residence time of liquid and particle could also be different (Legrand et al., 2007a,b). Consequently, it is possible for one phase to heat more rapidly, so as to create a large temperature difference. If a temperature gradient appears between fluid and particle, a convective–conductive heat transfer, h_{fp} will be generated to reach a thermal balance between the two phases. In this case, the solid generates heat at a slower rate than the liquid and in another case, it could be exactly on the contrary. However in each configuration, a suitable holding section could balance the cooking efficiency and the mean temperature of the product.

The electrical conductivity of the suspension is affected by a combined effect of temperature and solid concentration (Figure 24.4). In a direct Joule effect heater, any heterogeneity in the suspension (e.g., capsule flow or settling) generates nonuniformity in the delivery of the electric field and in the heating rate (microbiological destruction, enzymatic inactivation, cooking). In the worst case, the suspension heterogeneity leads to the instability of electrical parameters and precludes the use of a direct Joule effect heater. The relative electrical conductivity of the mixture at different particle concentration and the flow behavior of the suspension will be determinant in the decision as to whether the direct Joule effect heater can be considered as a relevant technology or not.

24.3 THE FLOW OF SOLID–LIQUID SUSPENSION: CHARACTERIZATION AND CONSEQUENCES

From a scientific and industrial standpoint, it seems important to describe the flow of solid–liquid mixtures in order to design a continuous process and to ensure that solid and liquid phases are

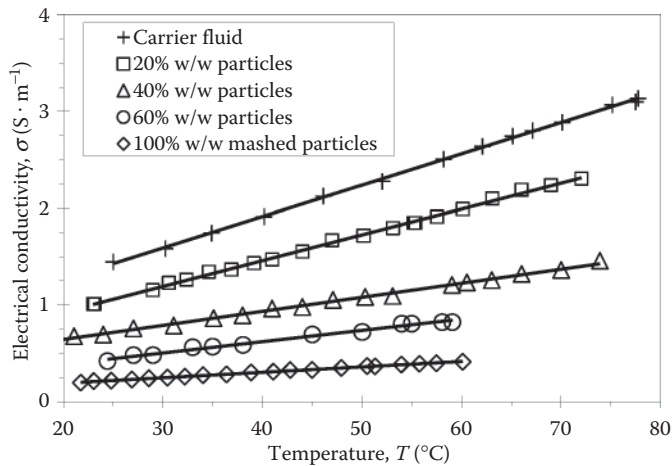


FIGURE 24.4 Electrical conductivity versus temperature and particle concentrations (carrier fluid: model tomato sauce 73% w/w water, 0.60% w/w xanthangum, 22.6% w/w sugar and 1.5% w/w NaCl salt, particles: blanched red bean). (From Legrand, A. 2005. *Faisabilité technologique du traitement thermique en continu de fluides en particules en utilisant trois technologies de chauffage*. PhD thesis, Université de Technologie de Compiègne, France. With permission.)

safe. However, the prediction of particle behavior in ducts remains a very complex problem (Figure 24.1—Hydrodynamics). Over the last 20 years, a wide range of literature investigating food mixture flow, from different scientific aspects has become available including Lareo et al. (1997). From a general standpoint, the scientific literature deals with (i) theoretical analysis: force balance (Caulet et al., 1996), (ii) global hydrodynamic approach: friction curves (Fagla, 2002), and (iii) specific studies: description of suspension, relative velocity (particle to fluid) (Baptista et al., 1997a,b and Grabowski and Ramaswamy, 1995). Otherwise, the knowledge of how particles are transported in non-Newtonian fluids is still limited to visual observations and qualitative criteria (Okuda, 1981; Sastry and Zuritz, 1987; Grabowski and Ramaswamy, 1995; Fagla, 2002). However, the criteria used are generally subjective (even if the distinction between a stationary bed and homogeneous suspension is obvious) and may refer to suspension heterogeneity and particle movement. For example, Sastry and Zuritz (1987) identified five types of solid–liquid flow: homogeneous, heterogeneous, intermediate, saltation, and capsule flow. Homogeneous flow is described as a uniform suspension throughout the cross-section. Heterogeneous flow occurs when particles are coarse. The solid–liquid phases are then separated and large density gradients exist in the flow. Intermediate flow occurs when conditions for heterogeneous and homogeneous flow exist simultaneously. Saltation flow occurs when the particles move from a bed at the bottom of the pipe and proceed in discontinuous jumps. Capsule flow occurs when solids are packed into cylindrical capsules and transported in series.

The effects of particle density and concentration as well as viscosity and flow rate on the distribution of the particles are, not as yet, well known. No quantitative criterion is available in literature to describe the particle distribution in the cross section. However, semi-empirical correlations between conventional dimensionless numbers have been established (Table 24.1). It seems useful (technologically and scientifically) to describe the state of a suspension from objective quantitative criteria (Fillaudeau et al., 2003; Legrand et al., 2004a,b).

24.3.1 A GEOMETRIC ANALYSIS OF THE SUSPENSION

Concentration versus height of a settling bed is described from a bed of discrete particles in a cylindrical duct. A suspension (fluid and spherical particles) flowing in a cylindrical tube is considered.

TABLE 24.1**Classical Dimensionless Numbers to Describe the Flow of Solid–Fluid Suspension**

Number	Definition	Meaning
Archimedes	$Ar = \frac{r_f \cdot d_p^3 \cdot g \cdot (r_p - r_f)}{m^2}$	$\frac{(\text{inertia force}) \cdot (\text{gravity force})}{(\text{viscous force})^2}$
Froude	$Fr = \frac{u^2}{g \cdot d_p \cdot (r_p - r_f / r_f)}$	$\frac{\text{inertia force}}{\text{gravity force}}$
Drag coefficient	$Cx = \frac{(r_p - r_f) \cdot g \cdot d_p}{r_p \cdot u^2}$	$\frac{\text{gravity force}}{\text{inertia force}}$
Reynolds	$Re_g = \frac{d_p^n \cdot u^{2-n} \cdot r_f}{k \cdot (3n + 1 / 4n)^n \cdot 8^{n-1}}$	$\frac{\text{inertia force}}{\text{viscous force}}$
Reynolds (suspension)	$Re_{\text{eff}} = \frac{D_c \cdot u \cdot r_f}{m_{\text{eff}}}$	$\frac{\text{inertia force}}{\text{viscous force}}$
Simplex	$a = \frac{r_p - r_f}{r_f}$	—
Diameter ratio	$f = \frac{d_p}{D_c}$	—

Homogeneous particles forming a stationary bed are assumed. A mathematical expression of bed height based on geometric description was determined, as well as the maximal and minimal admissible concentrations in the duct to form a homogeneous bed there. This bed is characterized by porosity, ϵ , corresponding to the liquid fraction of the bed divided by the total volume (particles and fluid). The volume of the settling bed may be expressed from geometrical variables, where h represents the height of the stationary bed. We gave an expression of particle concentration, C_p , versus h and vice versa, where, h is the minimal height of a bed according to particle concentration. This relation assumes homogeneous suspension without taking into account the notion of discrete particles.

$$C_p = \frac{(1 - \epsilon)}{p} \cdot \left[\text{Arc cos} \left(\frac{r - h}{r} \right) - \left(\frac{r - h}{r^2} \right) \cdot \sqrt{r^2 - (r - h)^2} \right] \quad (24.1)$$

The maximum concentration corresponds to a bed height equal to the tube diameter. It is determined with the porosity ($C_{p_{\text{max}}} = 1 - \epsilon$). The minimal particle concentration necessary to obtain a uniform bed, by supposing a total decantation can be determined. Knowing the particle diameter for the product, a minimum bed height equal to the particle diameter is considered.

The cumulative distribution of particles is obtained from the particle frequencies as shown in Figure 24.5, and quantitative criteria (y_{50}^* , y_{10}^* , h_{50}^* , and h_{10}^*) can be deduced. To accurately investigate the effect of experimental conditions (concentration, flow rate, orientation and diameter of tubes) on the flow of the suspension, two values, y_{50}^* and y_{10}^* , are defined as the relative heights of population at 50% and 90%, respectively. For each experimental condition, the concentration and the porosity of the particle beds allowed us to define two criteria for each particle concentration, h_{50}^* and h_{10}^* , respectively, as the half height of the particle bed and the height of the particle when particles are settling. These values can be established for limit conditions, which are those of homogeneous, heterogeneous suspensions, and stationary beds (settling) corrected according to particle radius as reported in Table 24.2.

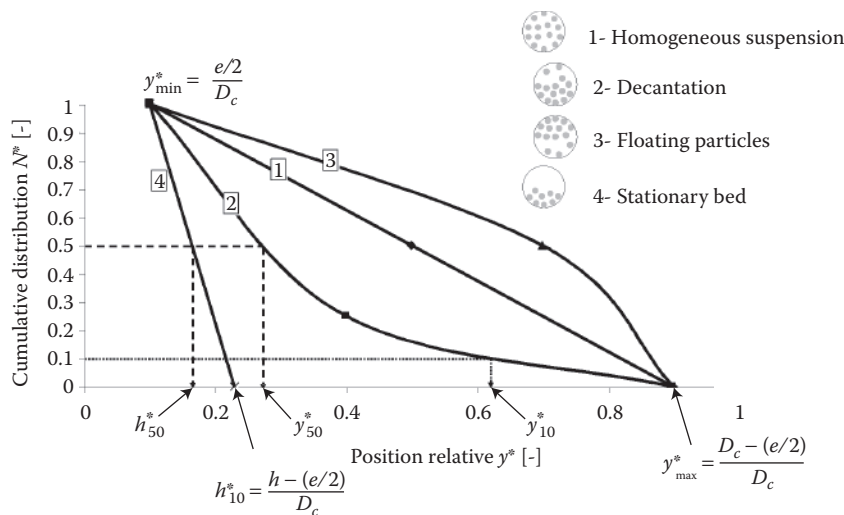
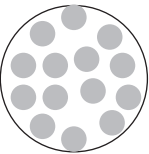
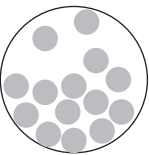
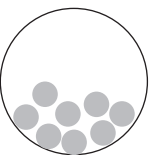


FIGURE 24.5 Cumulative distribution of particles versus relative position for different types of solid–liquid flow: particles flowing in a cylindrical straight smooth tube. (From Fillaudeau, L. et al., *Ecoulement des fluides agroalimentaires contenant de grosses particules: Méthode d’analyse de la distribution cumulée en particules dans des conduites cylindriques. Proceedings of 9ieme congrès SFGP (Société Française de Génie des Procédés)*, St Nazaire, France, Copyright 2003; *Journal Food Engineering* 78, Legrand, A., Berthou, M., Fillaudeau, L., 345–355, Characterization of solid–liquid suspensions (real, large and non-spherical particles in non-Newtonian carrier fluid) flowing in horizontal and vertical pipes, Copyright 2007b, with permission from Elsevier.)

TABLE 24.2

Values of y_{50}^* , y_{10}^* , h_{50}^* , and h_{10}^* According to Different Suspension Types

Suspension	y_{50}^*	y_{10}^*
 Homogeneous	$y_{50}^* = 0.5$	$y_{10}^* \approx 1 - \frac{d_p}{2 \cdot D_c}$
 Heterogeneous	$0.5 > y_{50}^* > h_{50}^*$	$1 - \frac{d_p}{D_c} > y_{10}^* > h_{10}^*$
 Stationary bed (settling)	$y_{50}^* \approx h_{50}^* = \frac{h}{2D_c}$	$y_{10}^* \approx h_{10}^* = \frac{h - (d_p/2)}{D_c}$

24.3.2 THE INFLUENCE OF PARTICLE CONCENTRATION ($C_{P_{MAX}}$, $C_{P_{MIN}}$)

Theoretical and experimental values of the maximum particle concentration limits are calculated and experimentally identified. The theoretical maximum concentrations corresponded to a bed height equal to the pipe diameter. It will therefore be impossible to obtain higher particle concentrations and only represent a theoretical maximal concentration in straight ducts. However, the presence of many bends and obstacles (enlargement, reduction) in the process generally caused blocking as soon as the particle concentrations increase. The significant difference between the theoretical and experimental values could be explained by the properties of real particles. The motion of a particle within a carrier fluid is affected by size, density, shape, and surface texture. Overall, properties help to define several recommendations, with regards to the continuous suspension processing. First of all, particle dimension may increase during the process, so that volume concentration at the outlet should be superior to that at the inlet in order to avoid blocking during the process. Second, mechanical properties will define the ability of particles to flow through a pipe with mechanical collisions between particles and with the wall. Mechanical resistance and elasticity appear to be the major criteria. If the particles settle below the minimal concentrations, they will never be able to form a uniform bed. This minimal concentration increases when the pipe diameter decreases, because of the porosity reduction. In a bigger pipe diameter, the particles will form a continuous bed with lower concentrations than in a smaller pipe diameter, which modifies the interactions between particles, and thus the flow behavior.

24.3.3 CONTINUOUS PROCESS: INTERACTION BETWEEN SUSPENSION FLOW AND HEAT TRANSFER

During continuous processing of solid–liquid suspension, some particles may travel close to the tube wall with a high residence time, whereas the carrier fluid flows in the upper part of the tube. Sterilization of such a suspension appears complex. This phenomenon does not make it easier to generate regular heating conditions and it disturbs the sterilization of the particle-charged fluid. However, it is necessary to ensure that each part of the product is sterile, without any part being overcooked.

The role of flow distribution information in the design of aseptic processing systems is not only to indicate how the particles stay in the system, but also to indicate the extent of the convective heat transfer from the fluid to the particles, h_{fp} . The local value of the heat transfer coefficient is strongly influenced by the cross-sectional distribution of the solid phase in the pipe (Fagla, 2002). In some cases, this phenomenon may cause local overheating. When the moving bed pattern is considered, the heat transfer increases above the bed by the mixing effect of the particles (Figure 24.6—Product B). In a direct Joule effect heater, the local heating rate is a function of the electrical conductivity of solids and the surrounding fluid. When the electrical conductivity of two phases is widely different, it is possible for one phase to heat more rapidly so as to create a large temperature difference between it and the other phase. For all of these technologies, any heterogeneity of the suspension in the delivery of the electric field generates nonuniformity in the heating rate (microbial destruction, enzymatic inactivation, cooking).

In the case of a homogeneous suspension (high concentration), the local value of the heat-transfer coefficient should be homogeneous (Figure 24.6—Product A). However, conventional thermal processing can be successful for single-phase fluids, but is limited in its applicability to multiphase foods. In this case, the time required to conduct heat to and from the centers of particles during a process could be a limiting factor.

24.4 HEAT TRANSFER: IMPACT OF SOLID PHASE

From a fundamental point of view, direct resistance heating of liquids is a complex physical problem in which a strong interaction between heat transfer, hydrodynamic, and electric phenomena can be observed (Ould-El-Moctar et al., 1993). Thermal behavior of solid–liquid food mixture flowing in a

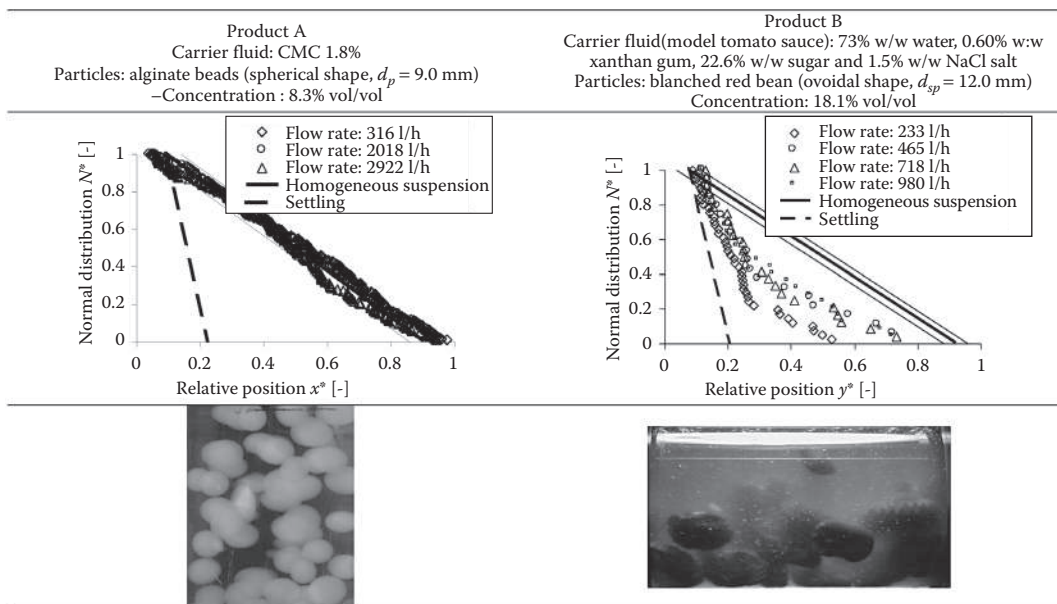


FIGURE 24.6 Cumulative distributions of particles and illustrations of quasi-homogeneous (Product A, horizontal duct, $D_c = 36$ mm, $C_p = 8.3\%$ v/v, $Q = 500$ L h⁻¹) and heterogeneous (Product B, vertical duct, $D_c = 48$ mm, $C_p = 18.1\%$ v/v, $Q = 2922$ L h⁻¹) suspensions. (From *Journal Food Engineering* 78, Legrand, A., Berthou, M., Fillaudeau, L., 345–355, Characterization of solid–liquid suspensions (real, large and non-spherical particles in non-Newtonian carrier fluid) flowing in horizontal and vertical pipes, Copyright 2007b, with permission from Elsevier.)

tubular Ohmic heater gives rise to a complex situation. Food particles are often large and high solid volume fractions are usual, thereby increasing the inter particle and particle–wall interactions. Electric field is strongly modified if the electrical conductivities of the solid and liquid phases are different and evolve differently versus temperature. In addition, thermal profiles of components are directly influenced by the liquid–particle, particle–wall, and liquid–wall heat exchanges (Benabderrahmane and Pain, 2000). For a solid–liquid mixture, where two phases have different conductivities, heat generation equation is valid only locally, and is dependent on the local arrangement of the particles and their volume fraction. Heterogeneity within solid and liquid heat generates a conductive–convective heat transfer between both the phases. The convective heat-transfer coefficient at particle surface, h_{fp} , constitutes a vital parameter to estimate the cooking and sterilization efficiency. Many workers, as reported by Barigou et al. (1998) and Baptista et al. (1997a,b), have developed dimensionless correlations relating Reynolds, Prandtl, and Nusselt numbers. The velocity that controls the interfacial heat transfer will be the relative velocity between particles and fluid (i.e., slip velocity) as well as particle rotation. In real mixture, h_{fp} is often unknown and hazardous to define.

Thermal homogeneity in Ohmic heating has been extensively investigated with homogeneous fluid and solid–liquid suspension in batch and continuous process. Experiments (Table 24.3) report local temperature measurements (insulated thermocouple, optical fiber, magnetic resonance imaging) or numerical simulations (home-made code, commercial FEM software) to get a simultaneous solution of flow, temperature, and electric fields. Zareifard et al. (2003) reported that many factors affect the heating rate of foods undergoing Ohmic heating: electrical conductivities of fluid and particles, specific heat, particle size, shape, and concentration as well as particle orientation in the electric fields (Kim et al., 1996). Sastry (1992) and Zhang and Fryer (1994) proposed a way to express in a macroscopic manner, the internal heat generation inside each material of the mixture. Davies et al. (1999) noted that homogeneity in the heating rate is crucial to ensuring uniformity of local heating

TABLE 24.3**Experimental and Analytical Investigation of Temperature Profile during Batch or Continuous Ohmic Heating of Homogeneous Liquid and Solid–Liquid Suspension**

Process	Homogeneous Liquid	Solid-Liquid Suspension
Batch	<p>Analytical expression of bulk temperature</p> <p>Numerical simulation:</p> <p>Local measurements (ThC, fiber optique): Li et al. (2004), Marcotte et Piette (1998), Kong et al. (2008)</p>	<p>Differential equations (coupling between electric and heat transfer)</p> <p>Numerical simulation: Sastry and Palaniappan (1992), Sastry and Salengke (1998), Fu and Hsieh (1999), Davies et al. (1999), Ye et al. (2004), Jun and Sastry (2005), Marra et al. (2009), Sastry et al. (2009).</p> <p>Measures locales (ThC, fiber optique): Zareifard et al. (2003), Zhong and Lima (2003), Ozkan et al. (2004), Sensoy and Sastry (2004)</p> <p>Measures globales (MRI), Ye et al. (2003 and 2004).</p>
Continuous	<p>Differential equations (coupling between hydrodynamic, electric and heat transfer) and analytical expression of bulk temperature.</p> <p>Numerical simulation: Ould-El-Moctar (1992), Quarini (1995), El-Hajal (1997), Ivory (2000), Marcotte et al. (2004), Leizerson and Shimoni (2004).</p> <p>Experiments with liquid food: Fillaudeau et al. (2001, 2004, 2006), Ghnimi et al. (2009a,b), Bansal and Chen (2006).</p>	<p>Differential equations: (coupling between hydrodynamic, electric and heat transfer)</p> <p>Numerical simulation: De Alwis and Fryer (1992), Benabderrahmane and Pain (2000).</p> <p>Experiments with food matrices: Yang et al. (1997), Eliot-Godereaux et al. (2001a,b), Legrand (2005).</p>

rate. They showed that the presence of any electrical insulator within the system creates a region in which heating rates are different. Therefore, care must be taken with the preparation of formulations for Ohmic heating processes. Benabderrahmane and Pain (2000) developed a model simulating thermal behavior of a solid–liquid system and demonstrated the influence in inhomogeneous electrical conductivity on heating of material. Eliot-Godereaux et al. (2001a,b) demonstrated the time passage distribution of particles in an Ohmic heating system, and proposed to estimate minimum lethality by recording the temperature profile of the liquid phase. Recently, Legrand (2005) compared the thermal profiles versus radius along a tubular Ohmic heater during the flow of a non-Newtonian carrier fluid, with and without particles (50% vol/vol meat particles). It highlights and demonstrates the beneficial effects of high particle concentration as long as the suspension flow is homogeneous (Figure 24.7). In Chapter 14, Ghnimi and Fillaudeau described available commercial systems and reported recent industrial applications of tubular Ohmic heating of solid–liquid food mixture.

24.5 CONCLUSIONS

The passage from a batch to a continuous thermal process for the sterilization of heterogeneous products, notably suspensions of fragile particles in viscous carrier fluids, remains an empirical and random operation even with alternative technologies such as Ohmic heating. An HTST is feasible but requires a perfect knowledge of the properties of both phases (carrier fluid and particles properties).

The physical (density, shape and dimensions, rheological properties), mechanical (elasticity modulus, maximal deformation, and stress) and thermal (heat capacity, thermal conductivity, thermal diffusivity) properties of particles are related to the moisture content, as are the electrical properties (electrical conductivity), which also strongly depend on temperature and the solid concentration.

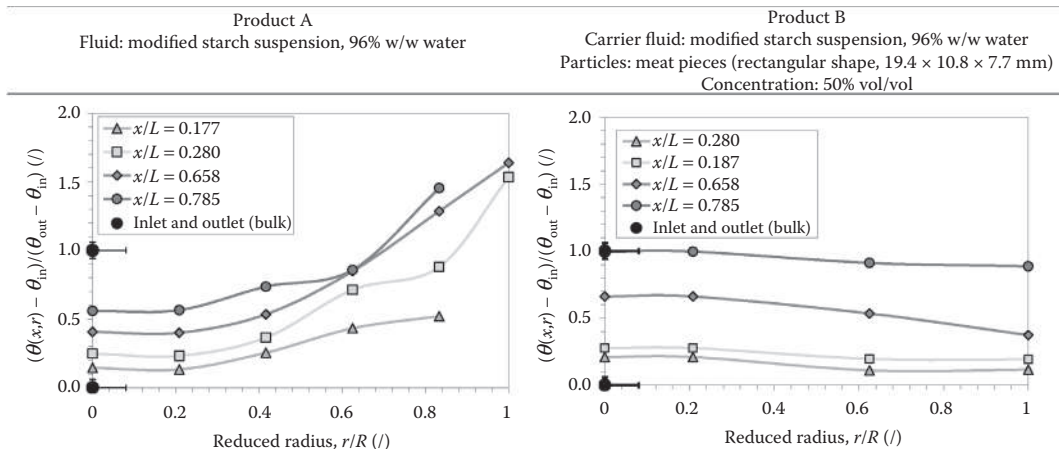


FIGURE 24.7 Radial distribution of reduced temperature along a tubular Ohmic heater ($L = 1125$ mm, $D = 48$ mm, $Q = 250$ kh/h, $P = 5$ kW, $\Delta\theta$ inlet–outlet $= \pm 18^\circ\text{C}$, $\text{Re}_{\text{Inlet}} = 1.2$) for a single phase (Product A: carrier fluid) and a solid–liquid suspension. (From Legrand, A. 2005. *Faisabilité technologique du traitement thermique en continu de fluides en particules en utilisant trois technologies de chauffage*. PhD thesis, Université de Technologie de Compiègne, France. With permission.)

All these properties need to be discussed by considering the flow behavior of the suspension, because all these properties interact closely with hydrodynamics. With a suspension composed of fragile particles in a carrier fluid, several points were identified as limiting factors for continuous heat treatment:

- The volume expansion of the particle increases the particle concentration (vol/vol) between inlet and outlet of the process and may affect the homogeneity of the suspension along the process.
- An important loss of mechanical properties enhances the physical degradation of particles.
- The large size of the particles and their complex shape associated with the loss of their mechanical properties could lead to extensive quality degradation of the product and induce duct plugging.
- Electrical conductivity is closely dependent on temperature and particle concentration, which may be important limiting factors during Ohmic heating. Any fluid overheating or suspension heterogeneity would lead to the instability of electrical parameters.

Considering suspension, although much information exists on solid–liquid flows, much of it relates to simplified flow situations (individual particles involving Newtonian fluids). The continuous treatment of suspension containing both liquid and large particles is to a great extent poorly understood, making the prediction of the form and the structure of the flows, difficult. Existing literature answers some of the specific points: the qualitative description of the suspension flow, the study of the residence time distribution (RTD) or the relative velocities particle to carrier fluid. On one hand, the dimensional analysis led to the establishment of several dimensionless numbers whose definitions may differ. On the other, no study describes the concentration profile in particles according to the height in the cross section. This point seems however, to be extremely important when quantifying the homogeneity and/or the heterogeneity of the suspension with the definition of quantitative criteria (y_{50}^* , y_{10}^*). Particle concentration profiles therefore provide additional information to RTD and relative fluid to particle velocities. These criteria may help to determine the influence of the several factors: suspension flow rate, particle concentration, the rheological

behavior of the carrier fluid, the inner diameter and orientation of the tube. The behavior of a real suspension characterized by a distribution of shape, dimension, density, mechanical properties could be very different to the behavior of a model suspension characterized by homogeneity of the same properties.

The heterogeneity or the settling suspensions have a simultaneous incidence on the suspension flow and the heat transfer. According to the type of technology adopted, specific problems can appear because of the heterogeneity of concentration profiles. Ohmic heating is defined as a purely volumetric and direct resistance heating, in opposition to heating by conduction from a hot surface heat exchanger. In consequence, the heat-transfer coefficient between the hot wall and the fluid is irrelevant, as there is no hot wall at all. The nonexistence of a hot wall should constitute a major advantage for food applications, thereby avoiding both the degradation of thermo-sensitive compounds through overheating (change in taste, undesirable reactions, burning) as well as reducing heat exchanger fouling). In spite of specific advantages due to the technology and recent industrial application, Ohmic heating could not be considered as a “Plug-and-Play” technology due to several critical factors.

NOMENCLATURE

LATIN LETTERS

Ar	Archimedes number (dimensionless)
Bi	Biot number, (/)
c	Specific heat ($\text{J kg}^{-1} \text{K}^{-1}$)
C_p	Particle concentration (% v/v)
C_x	Drag coefficient (/)
D, d	Diameter (m)
e	Thickness (m)
E	Elastic modulus (Pa)
$f(x)$	Normal distribution function (/)
$F(x)$	Cumulative normal distribution function (/)
Fr	Froude number (dimensionless)
g	Acceleration of gravity (9.81 m s^{-2})
h	Bed height of particles settling (m)
h_{10}^*	Bed height settling to 90% of the population (dimensionless)
h_{50}^*	Bed height settling to 50% of the population (dimensionless)
k	Consistency index (Pa s^n)
l	Width (m)
L	Length (m)
n	Flow behavior index (dimensionless)
$n_{\text{H}_2\text{O}}$	Absolute moisture content ($\text{g H}_2\text{O/g DM}$)
N^*	Cumulative distribution (dimensionless)
P	Power (W)
Q	Flowrate ($\text{m}^3 \text{s}^{-1}$) or (L h^{-1})
r	radius (m)
Re_g	Generalized Reynolds number (dimensionless)
T	Temperature ($^{\circ}\text{C}$)
v	Suspension velocity (m s^{-1})
x, y	Absolute position of particle center with vertical and horizontal duct (m)
x^*, y^*	Relative position of particle center (dimensionless)
x_{10}^*, y_{10}^*	Bed height to 90% of the population (dimensionless)
x_{50}^*, y_{50}^*	Bed height to 50% of the population (dimensionless)

GREEK LETTERS

α	Density simplex (/)
μ	Apparent viscosity (Pa s)
ρ	Density (kg m ⁻³)
ε	Porosity (dimensionless)
λ	Thermal conductivity (W m ⁻¹ °C ⁻¹)
ε	Maximum deformation (%)
σ	Electrical conductivity (S m ⁻¹)
τ	Stress (Pa)

SUBSCRIPTS

c	Duct
f	Fluid
p	Particle
sp	Equivalent to a sphere
max	Maximum
min	Minimum
In	Inlet
Out	Outlet

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25 Ohmic Heating for Space Applications

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25.1 INTRODUCTION

One of the more interesting applications that have emerged in the early twenty-first century is the potential for Ohmic heating in long-duration space missions. Interest has grown in mankind's future in space, with attention being given to a potential lunar base, and manned missions to Mars. Such missions are likely to pose major challenges to life support functions aboard space vehicles.

Long-duration space missions (e.g., International Space Station) and future interplanetary missions are completely different from their short-duration counterparts (e.g., space shuttle) in terms of psychological effects on crew members (Holland, 2002). Long-duration missions are characterized by gradual and ongoing psychological abrasion over time. Stressors include long-term confinement; separation from culture, planet, home, family, and sources of emotional support; inability to vent (emotionally); lack of variety, and tedium. In addition, disruptive events on orbit and earth can take a severe toll on crew members.

In this context, food becomes a very important component of the crew's routine. Holland (2002) details a number of the behavioral changes observed in crew, including a heightened awareness of types of foods, their availability, individuals' dietary preferences, increased interest in preparation and consumption, and the increased importance of food in social cohesion.

Meal times are often used for social and work discussion; eating is a bridge back to one's own culture and region.

A further challenge to the food supply system is the need for a five-year shelf-life at temperatures normally associated with human comfort—on earth this is commonly considered “ambient” temperature. This necessitates a supply of sterile, packaged food of high quality. Currently, foods are supplied to crew members in military Meals Ready-to-Eat (MRE) style pouches that are retorted prior to loading on space vehicles; however, for long-duration missions, higher quality food will be

needed. This is a potential opportunity for Ohmic heating within food packages, since the same cold-spot limitations do not exist.

Other challenges abound during transit. Foods must be heated to serving temperature in an energy-efficient manner. Thereafter, packages must be reused, recycled, or jettisoned, according to mission plans. Each of these options poses significant challenges. Recycling is not simple, a likely energy-intensive operation that raises Equivalent System Mass (ESM) (discussed later). Given that packages have to meet exacting barrier requirements, which are currently only met by metal foil layers, package biodegradability does not appear to be an option. Jettison is necessary with waste that cannot otherwise be handled on board; however, to conserve oxygen it cannot be done too frequently.

A critical element relates to ESM. Since the cost of putting 1 kg into orbit is in the range of US\$ 22,000, every item that is on board spacecraft must be viewed in the context of its effect on the mass of the entire space vehicle. For example, if a device is placed within the vehicle, its volume requires an increase in the overall system dimensions to accommodate it. Further, if the device consumes energy, it will require an increase in the power level of the energy source used in the vehicle. Conversely, if the device requires cooling, radiators outside the spacecraft must be resized accordingly. Thus, the addition of even small devices on board can incur severe mass penalties, resulting in a large ESM. These factors all need consideration in development of a space-based heating system.

25.2 OHMIC HEATING APPLICATIONS

Ohmic heating offers interesting advantages in a spacecraft environment. It has the unique advantage that a product containing liquid, solid, or solid-liquid mixtures can, with proper formulation, be heated rapidly with a uniform thermal profile. This ensures significant quality retention in comparison to conventional thermal processing treatments, where heat transfer to the interior dictates process time, resulting in significant quality loss. Ohmic heating will also eliminate bacterial spores. Ohmic heating has the advantage over microwaves of higher efficiency (>90%, compared to about 50% for microwaves), a more uniform and easily predictable electric field distribution; thus, the most minimally processed locations may be identified with greater confidence than microwave or radiofrequency heating. However, for Ohmic heating to be successful, the food should possess at least a slight electrical conductivity. Since fats and oils do not conduct electricity, Ohmic heating cannot be used specifically for these products.

In transit, Ohmic heating could be used to heat food. The system is lightweight, requires only an electrical power supply, and food packages that can be accommodated between electrodes. Space requirements are therefore minimal in comparison to most other heating technologies (it has been used for vending and dispensing applications). It is also suited to the available energy sources (electricity) in transit, which can be turned on or off at will. Therefore, this technology can be used for simple heating of foods for consumption. Ohmic heating may be well suited for a lunar or planetary surface-processing device, due to its simplicity. On the planetary or lunar surface, Ohmic heating may be used to create products (e.g., tomato sauce, vegetable purees), which can be sterilized and held for future consumption. This approach may also be useful in sterilizing any excess plant food harvest, which cannot be consumed immediately, but may need storage prior to future consumption.

25.3 OHMIC HEATING PACKAGES FOR LONG-DURATION SPACE MISSIONS

In a recent project funded by NASA, a container was developed which also functioned as an Ohmic heating device when an electric field was applied across. This enables the food to either be reheated (for an exploration mission), or sterilized (for an evolved Mars base) within it. The container is also made reusable; thus, after food is consumed, it could be used to contain biological waste, including human fecal waste. The container could then be sealed, subjected to an Ohmic sterilization process, and stored until jettison or return, depending on the mission plan. This effectively turns a potential

problem (handling of used food containers) into a solution, which would not only reduce the mass of waste storage containers necessary, but also provide a compact solution to waste sterilization and containment.

25.3.1 FEASIBILITY

The feasibility of container reuse can be justified based on the nominal metabolic interface values for crew members (Hanford and Ewert, 2002). The total mass balance on a human being suggests that the total food dry matter intake (0.617 kg/CM-d solids,* and 3.909 kg of water) is in significant excess of the potential solid waste load. Even if it is assumed that all the fecal waste (dry solids plus water) and the remaining human waste dry solids are stored, the total amounts to about 0.2 kg/CM-d. If the remaining water (perspiration, respiration, and urine) is recycled, the food container supply would more than suffice for accommodating human waste alone. In transit, the plan calls for ALS salad crops, which generate an additional inedible biomass level of 0.07 kg/CM-d (Hanford and Ewert, 2002), which is still well within the container volume available. On an evolved planetary base, where larger amounts of inedible biomass are produced, food container storage alone may not suffice. Nevertheless, the existence of surplus container capacity adds to the feasibility of this concept.

It is realized that not all waste is biological, and the unrecoverable components may require disposal or containment. Most of this waste may not require sterilization. However, some of it may be used as “filler” material, to help prevent buildup of an inventory of excess used food containers. In such cases, the material would be finely shredded and suspended within a homogenized continuous biological waste phase, which would then be filled and sterilized within the container. The electrical conductivity of the continuous biological waste phase could be sufficient to permit Ohmic heating. The ISS Increment Three waste generation rates (Hanford and Ewert, 2002), indicate that as much as 3.34 kg/CM-d of total waste is produced (excluding wastewater). Thus, it is prudent to assume that additional containment capacity (in addition to used food containers) will be necessary.

The energy requirements of a heating system would be the same regardless of the chosen technology, since the need is for food reheating, sterilization, waste processing, or water heating. While a genuinely valid ESM comparison between technologies requires more detailed data, we note that in comparison to two competing reheating technologies, (external electrical heating and microwave heating with the same power requirement), the Ohmic system volume will be significantly lower in volume; the energy conversion efficiency for Ohmic (conservatively 95%, Kern et al., 1995) is far higher than with microwave heating (65% at best; Saltiel and Datta, 1999), and the heat rejection penalty is lower (due to lower heat loss). Crew times are probably comparable across technologies, (if the crew simply loads the food into the heater, and with a few strokes on a keypad, activates the heating technology to return at a later stage). For a Mars mission scenario, the two biggest weighting factors in determining ESM (Hanford and Ewert, 2002) are shielded volume and power requirements, for both of which, Ohmic heating holds a significant advantage. Notably, none of the competing technologies will work well for sterilization due to significant, uncontrollable nonuniformities in heating.

25.3.2 THE DEVELOPMENT OF AN OHMIC HEATING PACKAGE AND DEVICE

The original embodiments of the Ohmic package involved attachment of strips of stainless steel foil electrodes to form the assembly. Contact points to external circuitry were provided by metal foil tabs that protruded from and sealed the package (Figure 25.1).

While it was possible to process samples within this type of package, the thermal distributions were less than optimal (Jun and Sastry, 2005, 2007), thus redesign became necessary. This was accomplished by modification of the shape to a more rectangular configuration (Figure 25.2). However, this arrangement still had protruding tabs that needed to be eliminated. This was

* CM, crew member; d, day.



FIGURE 25.1 Original embodiment of Ohmic pouch with protruding electrode tabs.

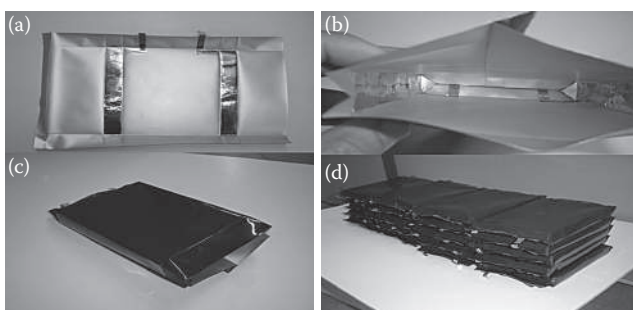


FIGURE 25.2 Redesigned pouch, showing rectangular geometry. (a) Electrode configuration, (b) folding, (c) unsealed assembly, and (d) sealed assembly.

accomplished by allowing the lead cables to pass through the pouch walls without contacting the metal foil layer (Sastry et al., 2011). Processing of materials was initially accomplished in an Ohmic “retort” assembly made of Ultem®, as shown in Figure 25.3. The retort operations consisted of those normally used in a conventional retort, except in that electrical energy was used instead of steam. Thus, there was no venting step, rather simply an application of power to the device, followed by a holding and a cooling phase under air overpressure to avoid seal breakage. This process was found satisfactory in ensuring seal integrity.

25.3.3 EFFICACY IN FOOD STERILIZATION

The rectangular-shaped pouch has been used for sterilizing foods. While a detailed discussion of the procedure and methodology are provided by Somavat et al. (2012a), we will present some key points here. To conduct verification experiments, a mathematical model was developed for heat transfer within the pouch during an Ohmic heating process. It was found that the zones near the walls on the nonelectrode sides were significantly cooler than the center of the pouch. To improve heating uniformity, external strip heaters were placed adjacent to the pouch, and were activated at

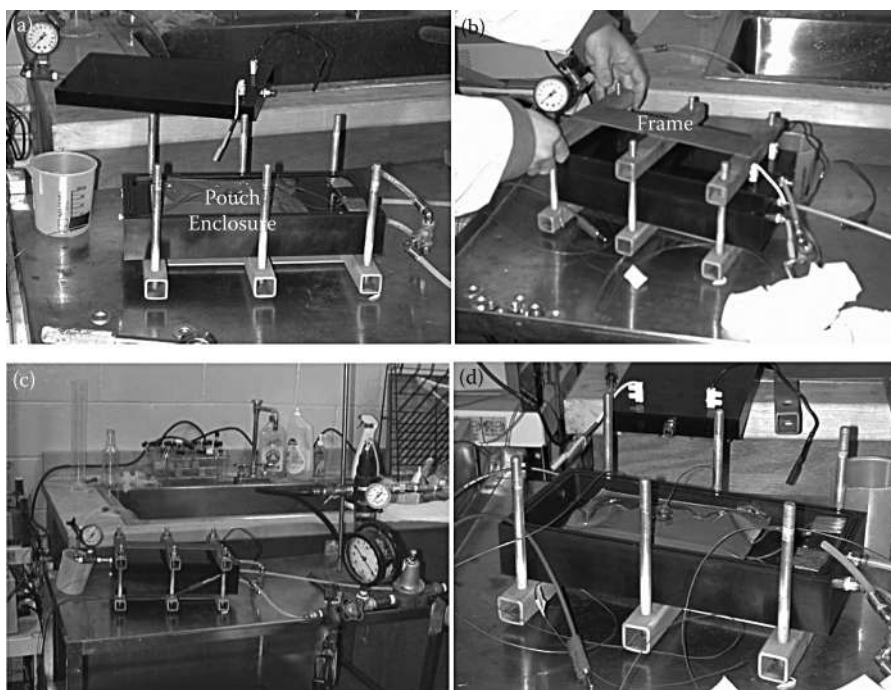


FIGURE 25.3 Ohmic retort operations: (a) loading, (b) closing, (c) processing, (d) post-cooling.

a specific stage of the thermal process. This helped greatly to improve heating uniformity, as determined by temperature measurement at various locations within the pouch. Model predictions were also found to be in agreement with measurements.

Finally, a microbiological verification test was conducted by inoculating a sample food with *Geobacillus stearothermophilus* spores and comparing predicted inactivation (based on a separate kinetics study by Somavat et al., 2012b) against experimental values. Again, good agreement was obtained, demonstrating the feasibility of relatively uniform pouch heating and its efficacy in sterilization. This suggests that Ohmic sterilization could be used to sterilize food prior to a long-duration mission to obtain potentially high-quality products.

25.3.4 THE MIGRATION OF ELECTRODE CONSTITUENTS INTO FOOD

A study was conducted (Jun et al., 2007) on migration of the major metal ions from stainless steel, such as Fe, Cr, Ni, Mn, and Mo, measured by inductively coupled plasma mass spectrometry (ICP-MS). Results show that pulsed Ohmic heating produced comparable or lower migration of most targeted metal ions, compared to conventional retorting when electrodes were present. The intakes of individual metal contaminants from a typical meal (8 oz) after Ohmic treatment were, as a maximum, 13.5% of published upper-level daily dietary exposure estimates (Ysart et al., 1999). Consequently, it was concluded that pouches with stainless-steel electrodes powered by a pulsed Ohmic heater show promise as a potential reheating and sterilization technology.

25.3.5 EFFICACY IN WASTE STERILIZATION

Studies were conducted on the sterilization of human waste in a pouch. The pouch was then stored successfully for over two years without issues with gas production. A photograph of the pouch 1.75 years after the sterilization treatment is shown in Figure 25.4.

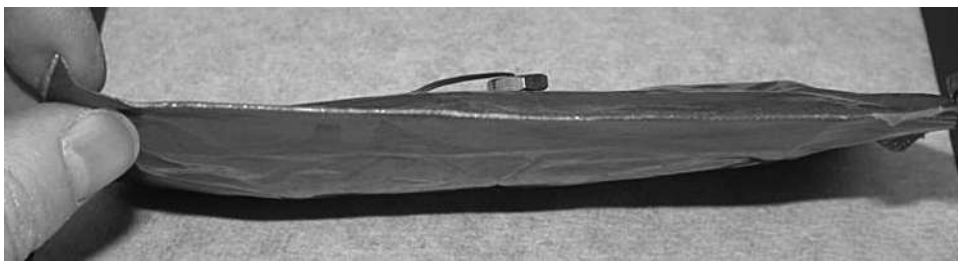


FIGURE 25.4 Pouch with human waste sterilized and stored for 1.75 years.

25.3.6 EFFICACY AS A FOOD WARMER

Electrical conductivity of a variety of products were determined to verify if it would be possible to heat a cross-section of products used by NASA. An example of electrical conductivity is presented in Figure 25.5 for Southwestern corn soup.

Results of heating tests indicated that four pouches of salt solution with 0.4% salt content could be heated within 25 min to the target temperature, at a power level of 200 W; well below the allowable 250 W. Tests were also conducted on a number of other products including tomato soup and cream of potato soup, and were able to heat these products within the required time and power constraints (Pandit et al., 2008).

An updated food warmer was developed as part of this effort, intended for improved convenience, and is shown in Figure 25.6. Another aspect of development of the warmer was the size of the electronic components involved. Figure 25.7 illustrates their small size.

25.3.7 EQUIVALENT SYSTEM MASS

The ESM concept arises from the need to design spacecraft as efficiently as possible, due to the high cost (US\$ 22,000/kg) of putting materials in orbit. Each item that is placed within a vehicle occupies space, which necessitates a corresponding increase in vehicle size to accommodate it. Further, if the item uses energy, or requires cooling, this will increase the demands on the power or cooling systems, increasing their mass. Consequently, each such factor results in an increase in system size, resulting in a mass penalty for each of the key aspects of the item. ESM is then the

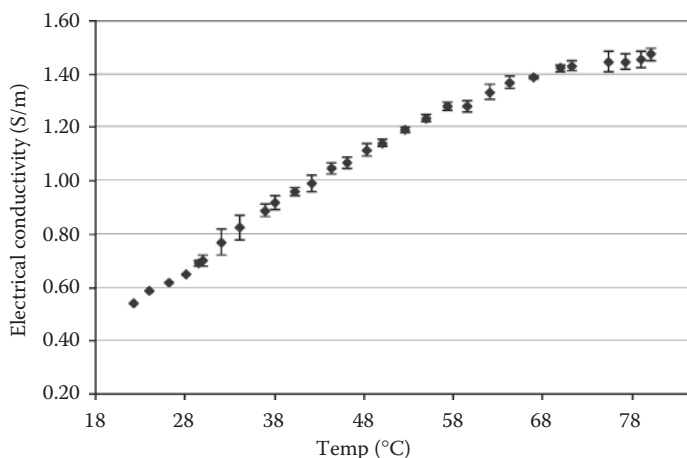


FIGURE 25.5 Electrical conductivity vs. temperature for Southwestern corn soup.

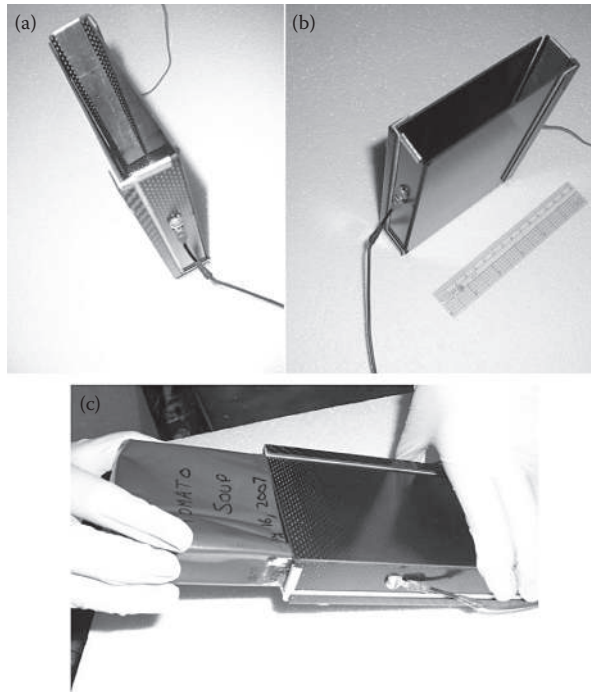


FIGURE 25.6 (a, b) Heater closure showing metal contact plates; (c) package being inserted into enclosure for heating.



FIGURE 25.7 Power electronics for heater. Left, DC voltage booster; right, IGBT module.

sum of the masses of life support supplied commodities, plus the mass penalties for infrastructure support, especially power, volume, cooling, and crew time required to operate and maintain the life support system (Levri et al., 2003).

ESM was calculated as

$$\text{ESM} = \sum_{i=1}^n \left[(\text{MI}_i \text{ SF}_{I_i}) + (V_{I_i} \cdot V_{eq_i}) + (P_i \cdot P_{eq_i}) + (C_i \cdot C_{eq_i}) + (\text{CT}_i \cdot D \cdot \text{CT}_{eq_i}) + (M_{TD_i} \cdot D \cdot \text{SF}_{TD_i}) + (V_{TD_i} \cdot D \cdot V_{eq_i}) \right]$$

where

i = number of subsystem consider in ESM calculation

MI_i = initial mass of subsystem i

SF_{I_i} = initial mass stowage factor for subsystems i (kg/kg)

V_{I_i} = initial volume of subsystem i (m³)

P_i = power requirement of subsystem i (kWe)

C_i = cooling requirement of the subsystem i (kW_{th})

CT_i = crew time requirement of subsystem i (CM-h/y)

D = duration of the mission segment of interest (y)

M_{TD_i} = time- or event-dependent mass of subsystem i (kg/y)

SF_{TD_i} = time-dependent mass stowage factor for subsystem i (kg/kg)

V_{TD_i} = time-dependent volume of subsystem i (m³)

$V_{eq_i}, P_{eq_i}, C_{eq_i}, \text{CT}_{eq_i}$ are corresponding mass equivalence factors.

The total ESM for the Mars Transit Vehicle in the Independent Exploration Mission for the Ohmic food warming unit was computed to compare our design with the existing suitcase-type heater (Pandit et al., 2008). For this assessment, the computed crew time–mass penalty was considered to be 0.728 kg/CM-h (Hanford, 2006). This ESM calculation is based upon a crew of six members consuming two meals daily. Mass of the food sample in each pouch was considered as 226 g. Other assumptions and equivalence factors were considered similar as mentioned by Hanford (2006) for the Mars Transit Vehicle.

The results show that the ESM for the Ohmic system was much lower (839 kg) (Pandit et al., 2008) than the existing suitcase-type heater (3475 kg) for the same mission (Rapp, 2006).

25.4 CONCLUSIONS

Ohmic heating has great potential for long-duration space missions, due to its high efficiency, compatibility with existing power sources on spacecraft, and compact design, resulting in reduced ESM in comparison to existing heating systems. Further, the concept of Ohmic packages is feasible, based on waste generation calculations in transit. Studies on sterilization of food and waste have been successful, suggesting the possibility of more widespread uses for the technology in space.

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26 Ohmic Cooking of Food

Mohammad M. Farid, Wei Jian Kong, and Necati Ozkan

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26.1 INTRODUCTION

Food preparation and safety are major issues in this modern world. These are especially important in the fast food sector. A hamburger patty, which plays a significant role in the modern diet, is a core member of fast food family. Hamburger patties are often cooked in industrial grills, between two heated plates. The patties are cooked while frozen to avoid any bacterial contamination that may occur during the thawing process. Due to the high latent heat of melting of ice, the center temperature of the patties may not rise to the necessary level for killing all pathogenic microorganisms. USDA-FSIS (1993) and FDA (1993) require that hamburger patties be cooked to 71°C and held for at least 15 s (Pan et al., 2000). Outbreaks of food poisoning have caused continuing interest in modifying the cooking method (Shipp et al., 1991; Ahmed et al., 1995; Jackson et al., 1996) and efforts have been made to understand the mechanism of heat and mass transfer during cooking of the meat patties (Pan et al., 2000).

Ohmic heating of fluids, which may also contain solid foods, has been thoroughly studied and reported in literature and will be covered in a number of other chapters in this book. However, the direct application of Ohmic heating to solid food is limited (de Alwis and Fryer, 1990) due to the difficulty in providing a good contact between the electrodes and the food surface.

The hamburger patties are usually flat, making their Ohmic heating application easy and requiring minimum modification to the existing equipment. Recently, a new method of cooking meat patties has been patented (Farid, 2001). The method is based on passing AC current through the meat patties generating heat throughout its whole thickness. The method was tested on a domestic sandwich plate

grill made by Breville (model number SG600B) followed by a rigorous testing on an industrial grill manufactured by Garland and usually used by the fast food industry such as McDonalds. The upper and lower plates of the grill were connected to an AC power supply, capable of providing any voltage below 240 V. The details of the design of the modified grill is given in this chapter.

This novel cooking method could offer a number of advantages, such as faster cooking, less power consumption, and safer product. However, the important considerations for a food product are its taste, quality, and customer satisfaction. Therefore, hamburger patties cooked by the combined Ohmic and plate heating were tested for quality and compared with those cooked by normal grill plates, as will be discussed in the following sections.

26.2 DETAILS OF THE MODIFICATIONS MADE FOR THE GARLAND INDUSTRIAL GRILL

26.2.1 MECHANICAL

The details of the modification carried out for the Breville grill is described elsewhere (Ozkan et al., 2004). The design that was chosen to modify the Garland grill consists of attaching metal plates to the top and bottom surfaces of the grill, held together by supports and insulating material to insulate the plates from the rest of the machine. The design of the supports allows the nondestructive modification to the grill. This can easily be taken apart by undoing the screws. There are four support blocks that are attached to the left and right side, top and bottom of the grill. Teflon nonbaking sheet used by fast food franchisers for nonsticking purposes were used as the insulating material. These were placed between the plates and the grill surface to electrically isolate other parts of the machine. The sheets were made larger so that they cover the plates during cooking, to prevent the danger of operators touching the plates during cooking. Figures 26.1 and 26.2 describe these modifications.

Materials used in the mechanical modifications consisted of:

- Plates: 5 mm thick stainless steel (top) and 3 mm thick stainless steel (bottom)
- Supports: Teflon blocks with screws
- Insulating material: Baking nonstick sheet used by fast food franchisers

26.2.2 ELECTRICAL

To incorporate the Ohmic cooking technology, the stainless-steel plates were connected to the secondary winding of an isolating transformer as shown in Figure 26.3. A safety circuit comprising of safety circuit breaker, an isolation switch, interlock switch, latching contractor, and a micro switch have been designed and added to the isolating transformer to address safety issues.

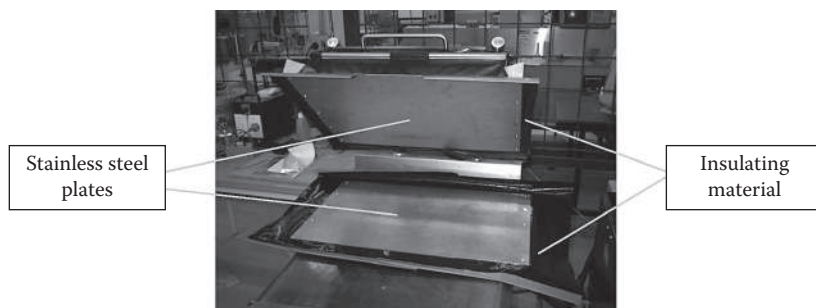


FIGURE 26.1 Mechanical modification of Garland grill. Here the plates and insulating material are visible.

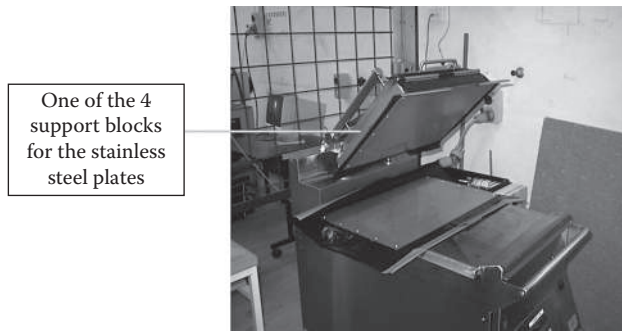


FIGURE 26.2 The grill after mechanical modification, showing a view of the Teflon support block.

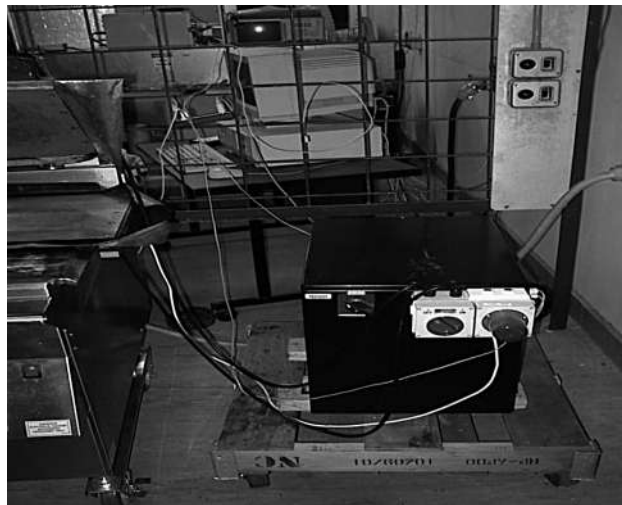


FIGURE 26.3 The isolating transformer and electrical connections.

Micro switch was designed so that the current is turned off when platen is in the “up” position. The safety circuit breaker was designed to turn off when the current reaches a preset value. The Ohmic cooking can be started with a push of a button on the isolating transformer, which is within easy reach. A red light will flash when Ohmic cooking is in progress. The experimental set up is shown in Figure 26.4.

26.2.3 THERMAL

The thermal resistance caused by bowing/bending of the plates resulted in a lower temperature on the cooking surface. The set temperatures for the 4:1 patties at Fast food franchisers are 220°C top plate and 170°C for the bottom plate. The temperatures achieved after modifications were only 205°C and 160°C, respectively, due to this thermal resistance. There were also temperature variations across different areas of the plates. This problem appears because only temporary changes were intended to be made to the grill machine. This will not be a problem when a new machine is designed. Below are some of the features of these modifications.



FIGURE 26.4 Experimental set up used for cooking.

26.3 EXPERIMENTAL PROCEDURE

26.3.1 MATERIALS

- Hamburger patties were prepared based on pure minced beef without the addition of any flavoring or preservatives in 115 g portions. The patties were designed to replicate the 4:1 (quarter pounder) patties used by fast food franchisers. All the hamburger used in the experiments was produced in a single batch to minimize variation in meat quality. The patties were frozen immediately after production with a pin inserted in the center of each of them to create a hole for thermocouple insertion.
- Oil: Peanut oil was used to prevent hamburger patties sticking to the surface of the grill.
- Thermocouples: 0.3 mm type K thermocouples were used to measure the center and surface temperatures of the meat patties during cooking. They were connected to a computer through a data logger to monitor the temperature continuously.

26.3.2 COOKING

- The cooking cycle of the hamburger patties was designed to replicate that used for the 4:1 patties in fast food franchisers.
- Cooking time was 104 s.
- Temperature of the grill was set to remain at 220°C and 170°C at the top and bottom surface, respectively. However, due to modifications made to the grill, this was not achieved. Tests carried out at the beginning of each run showed the top and bottom plate temperatures were about 205°C and 160°C, respectively, in the open position.
- Gap setting was set to 10 mm.
- The patties were cooked frozen straight out of the freezer.
- 20 mL of oil was used to prevent hamburger patties from sticking to the surface of the grill.
- The metal pin was removed from the patty prior to cooking and was replaced by thermocouples connected to the data logger. The other thermocouple was placed below the meat patties prior to the starting of the cooking.
- Ohmic cooking was carried out at 50 V.
- For quality testing, six patties were cooked in one run. For the Ohmic cooking, the patties were cooked for a shorter time to avoid overcooking the patties.

- For performance testing, two patties are cooked side by side. Half of the top plate has been covered with insulating material while the other half is left exposed. Ohmic cooking is usually begun by switching on the isolating transformer.
- The automatic cooking cycle was started by pressing the green and black button on the grill. The top plate will automatically move down on top of the patties. At the end of the cooking cycle (after 104 s), the top plate automatically lifts and the patties are removed.

26.3.3 SAMPLE PREPARATION

- Samples for mechanical testing needs to be prepared as quickly as possible after cooking, as food materials are quite sensitive to environmental conditions.
- A 32-mm-diameter pipe has been sharpened to function as a knife and used to create four circular samples per meat patty cooked by both methods.
- The circular samples were placed within a plastic bag and stored in a water bath (70°C) to be kept warm. These samples were then used for mechanical testing, while they were still warm.
- The remainder of the patty was sliced as thinly as possible and placed on a Petri dish to be used for moisture content testing.

26.3.4 MECHANICAL TESTS

- The samples were compression tested using an Instron testing machine (Instron 5567, UK) attached to a 200 N load cell tested in the Instron Machine.
- The samples were compressed at a rate of 2 mm/min into a maximum displacement of 3 mm and back to original position, using a 25-mm diameter circular plate. The force vs. displacement was recorded.
- The samples were precompressed to 0.5 N to standardize the samples. This was taken as zero. This was to account for the irregular shape of the each patty.

26.3.5 MOISTURE CONTENT

Moisture content in cooked meats is important because it has a significant influence on taste. It also reflects the degree of cooking, as insufficiently cooked patties will be moist, while overcooked patties will be hard.

After the meat patties were cooked and mechanically tested, the remaining beef patties were diced up into fine pieces ($5 \times 5 \text{ mm}^2$) and placed in an oven for 3 h at 105°C as described below. This setting is recommended in the literature (Warriss, 2000).

- Weigh six drying dishes and record their mass.
- Place 20 g of chopped up hamburger patty of each (approximate). Record combine mass of patty and dish before drying.
- Place drying dish in the drying oven for 3 h at 105°C.
- Remove drying dish from the oven and record the combined mass of patty and dish after drying.
- Place dried hamburger patty in a plastic to be used for fat content analysis.

26.3.6 FAT CONTENT

Fat content is an important property of the cooked meat patties. It is important that the newly developed combined Ohmic and plate cooking method does not lead to meat patties with higher fat content. In fact, efforts, nowadays, are focussed on reducing fat content in such products.

The Soxhlet extraction method adopted in this work is a common method to determine fat content in food products. The Soxhlet extraction set up consists of a heating plate, conical flasks, a Soxhlet extractor, and a condenser. The heating plate was used to vaporize the solvent (*n*-hexane) contained in the conical flasks. The condenser was used to condense the solvent (hexane) vapor. The steps used for measuring fat content are summarized as follows:

- Mix the six dried hamburger pieces together.
- Crush pieces into fine powder and sieve to get a consistent size distribution.
- Place 10 g of crushed meat samples in a thimble.
- Fat content analysis was evaluated by Soxhlet extraction. Equipment consists of: a heating plate, conical flask, Soxhlet extractor, and a condenser.
- Use 150 mL of hexane in the conical flask. Place the thimble of crushed meat samples in the Soxhlet extractor. Commence extraction by evaporating the hexane. Run extraction for 3.5 h.
- Weigh a bone dry beaker.
- Place thimble inside the beaker to allow the hexane to drain into the beaker. Pour hexane and extracted fat into the beaker.
- Weigh the beaker + hexane + extracted fat.
- Place beaker on heating plate to evaporate hexane.
- Weigh the beaker after the evaporation of hexane.

26.4 RESULTS AND DISCUSSION

26.4.1 COOKING TIME REDUCTION

The cooking time of the hamburger patties was defined as the time required for the center temperature of the patties to reach 70°C plus 15 s. The comparison of cooking time (Figure 26.5 and Table 26.1) shows that Ohmic cooking; when used with conventional cooking, can decrease the

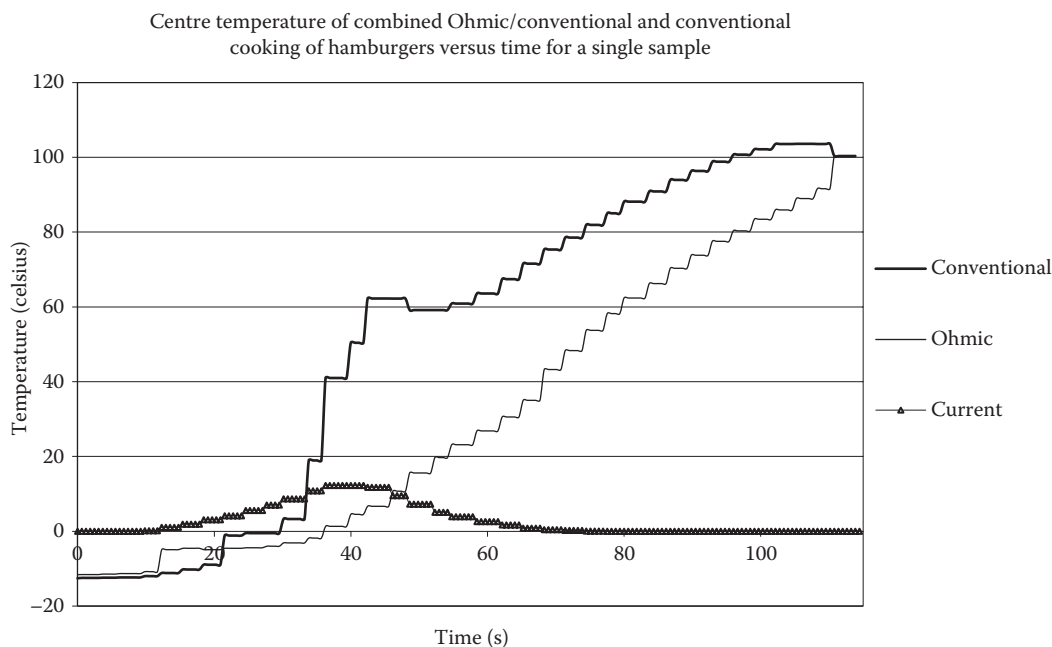


FIGURE 26.5 Center temperature of hamburger vs. time of combined Ohmic/conventional cooking and conventional cooking processes.

TABLE 26.1
Cooking Time Comparisons of Combine Ohmic/
Conventional and Conventional Cooking Processes

Run	Cooking Time (s)		Ratio of Combined vs Conventional
	Ohmic (s)	Conventional (s)	
1	69	96	0.719
2	54	111	0.486
3	88	—	—
4	65	95	0.684
5	51	91	0.560
6	61	—	—
	Mean		0.612
	Standard deviation		0.108
	90% Lower limit		0.507
	90% Upper limit		0.718
	<i>n</i>		4

cooking time by 50%. The mean cooking time using the combined cooking method was 65 s while it was 98 s for the conventional method. The individual difference gave a mean of 61% and a 90% confidence interval between 50% and 72%. While the sample size is small, it is clear that the addition of Ohmic cooking reduces the cooking time of hamburger. Larger time reduction is expected since the surface temperatures of the upper and lower plates of the grill were lower than the values set for normal cooking.

Examination of the cooking profile of the two cooking processes shows there are four different mechanisms (Figure 26.6):

- A. A slow cooking rate as the frozen patties melt. No Ohmic cooking occurs as when patties are frozen, little or no current flows through the patties.
- B. A high cooking rate as the Ohmic heating come into effect, dominates, and adds on to the conventional process.
- C. A plateau is reached as the surface of the hamburger patties browns thus preventing flow of current as the surface dries. Conventional heating dominates and the effect of Ohmic heating decreases with time.
- D. Conventional heating alone.

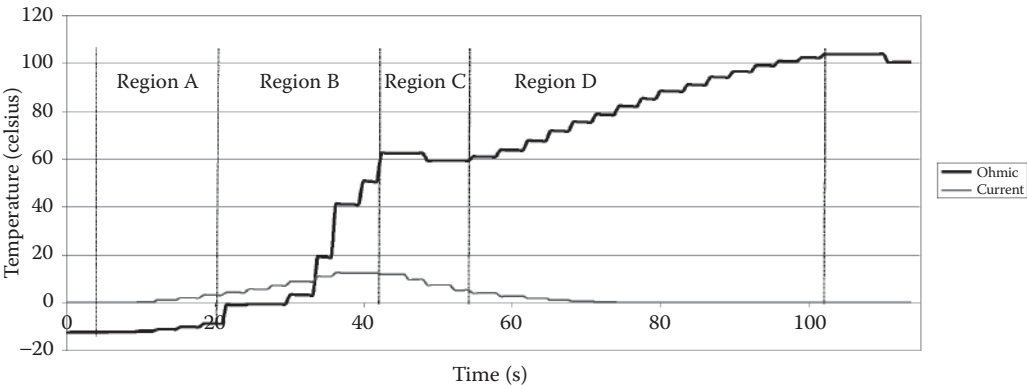


FIGURE 26.6 Temperature profile of combined Ohmic/conventional cooking of hamburger patties.

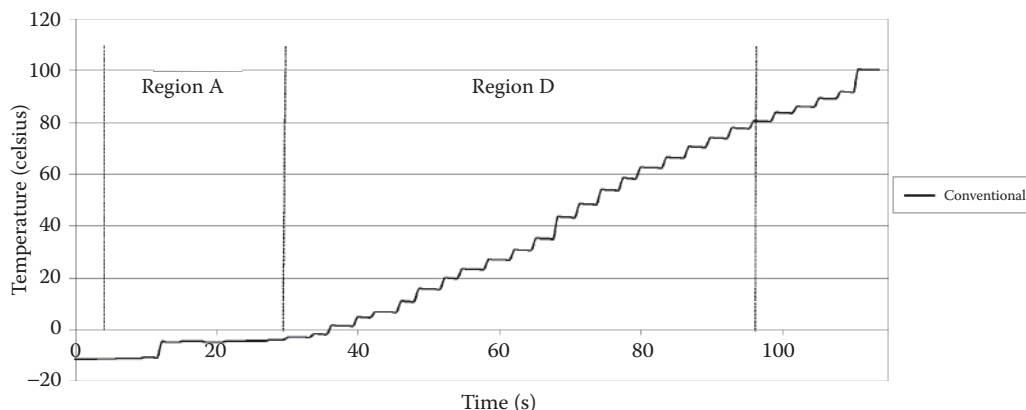


FIGURE 26.7 Temperature profile of combined Ohmic/conventional cooking of hamburger patties.

TABLE 26.2
Cooking Rate at Different Mechanisms
during the Cooking Process

Mechanism	Cooking Rate ($^{\circ}\text{C/s}$)	
	Combined	Conventional
A	0.34	0.38
B	5.38	—
C	-0.50	—
D	0.99	1.37

Ohmic cooking goes through the four mechanisms while in the conventional cooking; mechanisms B and C are absent, as shown in Figures 26.6 and 26.7.

Analysis of the results obtained is consistent with the observations. In region A, both Ohmic and combined heating yielded a similar cooking rate (Table 26.2) while the patties thaw. In region B, the combined effect of Ohmic and conventional heating achieved a cooking rate of nearly four times that of conventional alone. (In C, the rate dropped to negative, which may be due to the fact that the centers of the hamburger patties were being cooked mainly by Ohmic heating. Conventional cooking through conduction has not reached the center yet. The Ohmic process stops due to the browning of the patties (formation of crust), which explain the momentary drop in temperature. In region D of the Ohmic process, the cooking is by the conventional mechanism only and matches that of the conventional process. The measurement of mechanism D for Combined is in the last period of the process when the patty is dried.

26.4.2 QUALITY OF THE MEAT PATTIES

To verify quantitatively if Ohmic cooking causes any difference in the quality of hamburger patties; moisture content, fat content, and mechanical properties (hardness, elastic modulus, stiffness, and elasticity index) were measured for the meat patties cooked by the two methods.

The results obtained from the quality tests showed that the use of Ohmic cooking does not cause any significant changes to the mechanical properties (Table 26.3), moisture, or fat content (Table 26.4) of the cooked hamburger. The samples cooked with the combined method had lower

TABLE 26.3
Mechanical Testing of Hamburger Patties Cooked via Combined Ohmic/Conventional and Conventional Cooking Processes

		Combined	Conventional
Hardness (kPa)	Mean	66.3	71.4
	Standard deviation	22.9	21.9
	90% Lower	59.0	65.0
	90% Upper	73.5	77.7
	<i>n</i>	38	46
Elastic modulus (kPa)	Mean	33.3	34.7
	Standard deviation	11.1	9.2
	90% Lower	29.8	32.1
	90% Upper	36.8	37.4
	<i>n</i>	38	46
Elasticity index	Mean	0.368	0.377
	Standard deviation	0.029	0.031
	90% Lower	0.358	0.368
	90% Upper	0.377	0.386
	<i>n</i>	38	46
Stiffness (MPa)	Mean	6.48	6.40
	Standard deviation	3.47	2.07
	90% Lower	5.38	5.80
	90% Upper	7.58	7.00
	<i>n</i>	38	46

values of hardness and elastic modulus. There were no significant differences in the moisture content. The combined cooking method produced slightly lower fat content however; a larger number of samples is needed to confirm this result. In general, the results show that Ohmic cooking does not change food quality. This was confirmed through tasting, where there were no detectable differences. The small variations in the results are most likely caused by experimental and human errors.

TABLE 26.4
Moisture and Fat Content of Hamburger Patties Cooked via Combined Ohmic/Conventional and Conventional Cooking Processes

		Combined	Conventional
Moisture content (%)	Mean	56.9%	57.3%
	Standard deviation	2.8%	1.3%
	90% Lower	55.3%	56.6%
	90% Upper	58.4%	58.0%
	<i>n</i>	12	12
Fat content (%)	Mean	19.1%	19.8%
	Standard deviation	0.2%	0.3%
	90% Lower	18.9%	19.5%
	90% Upper	19.4%	20.2%
	<i>n</i>	3	3

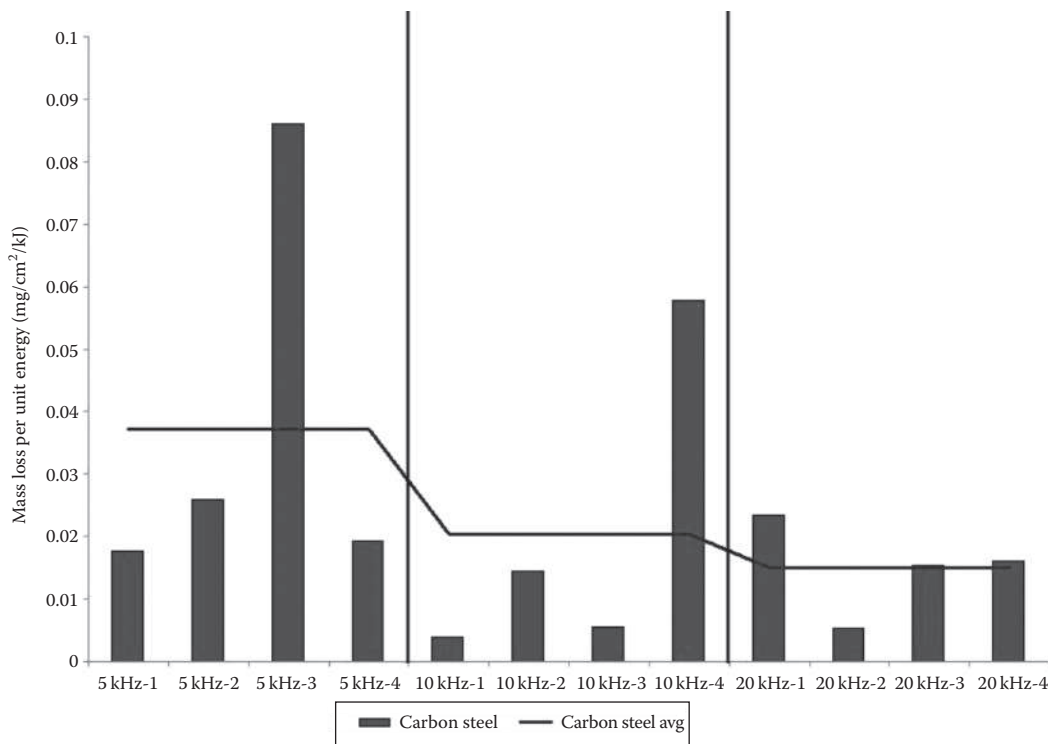


FIGURE 26.8 Mass loss from the steel plates using sinusoidal power supply at frequencies of 5, 10, and 20 kHz. The average results for each frequency shown by the horizontal lines in each third of the plot show a decreasing mass loss with increasing frequency.

26.4.3 CORROSION OF THE GRILL'S PLATES

To study corrosion of the heating plates during cooking, the modified Breville sandwich grill was used. The Ohmic cooker was connected to a 50 Hz power supply, while another power supply, built in the Department of Chemical and Materials Engineering, University of Auckland, New Zealand, was used to provide power at high frequencies (5, 10, and 20 kHz). The corrosion was not tested on the grill plates but rather on small and thin stainless-steel plates of 4×4 cm, screwed to the upper and lower plates of the grill so that they can be removed and tested for weight loss.

The meat patties were cut into squares 3×3 cm and cooked on the stainless-steel 316 plates. For all the above conditions, four sets of plates were tested for each condition to test repeatability. Four patties were then cooked on each plate to ensure that a measurable amount of pitting was obtained. The plates were cleaned and weighed before and after cooking. During cooking, the voltage and current readings were recorded every 10 s, and the cooking duration was 70–100 s.

The results of mass loss from the plates using a sinusoidal power supply of 50 Hz resulted in the largest rate of mass loss at $0.314 \text{ mg cm}^{-2} \text{ kJ}^{-1}$. The mass loss decreased as frequency increased approaching $0.01 \text{ mg cm}^{-2} \text{ kJ}^{-1}$ at a frequency of 20 kHz as shown in Figure 26.8. This suggests that high-frequency current should be applied for safety and to ensure long life of the cooking plates.

26.5 CONCLUSION

The application of combined Ohmic and plate cooking of hamburger patties was found very successful in reducing cooking time and for producing safer products. Cooking time comparisons showed that combined Ohmic/conventional cooking reduces the cooking time of hamburger patties

at an average of 61% of conventional. Further reduction is possible by increasing the applied voltage. Quality tests of the meat patties cooked by the newly developed method and the conventional method showed similar moisture and fat contents. Also the mechanical properties of the two products were very similar.

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27 Electrofreezing

Marta Orlowska, Alain LeBail, and Michel Havet

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27.1 INTRODUCTION

Refrigeration of food products, that is, cold storage and freezing, are the most popular methods used in preservation of seasonal foods and for cutting food loss. This chapter presents improvement of refrigeration processes by development of innovative methods with the application of high-voltage electrostatic field (HVEF). For better understanding of the importance of the innovations, first described are the basics of water properties and conventional methods of freezing. These are followed by the theoretical and experimental studies on electrofreezing, freezing under combined electrostatic and magnetic fields, electrothawing, and finally storage under HVEF conditions.

27.2 A FEW WORDS ABOUT WATER PROPERTIES

Water is a tiny V-shaped molecule with molecular diameter about 2.75 Å. It consists of two light hydrogen atoms and one approximately 16-fold heavier oxygen atom (Chaplin, 2008). The oxygen atom forms two covalent sigma (σ) bonds (40% partial ionic character), each of which has dissociation energy of 4.6×10^2 kJ/mol (Fennema, 1996). Both O–H bonds are formed by the overlap of a sp^3 orbital of oxygen with the s orbital of a hydrogen. Each of the two remaining nonbonding sp^3 orbitals on O-atom is occupied by two lone-pair electrons. The O–H internuclear distance is 0.96 Å and the van der Waals radii for oxygen and hydrogen are 1.40 and 1.2 Å, respectively (Fennema, 1996; Finney, 2004; Maréchal, 2007; Chaplin, 2008). The average internal H–O–H angle of the isolated water molecule in the vapor state is 104.5°. This is close to both the tetrahedral angle (109.478°) and the internal angle of a planar pentagon (108°). Usually the geometry of a water molecule is described by the ideal tetrahedral arrangement of sp^3 -hybridized electron where each water molecule should be surrounded by four hydrogen-bonded neighbors, as it is shown in Figure 27.1. However within the liquid water structure, significant population of threefold local coordinations,

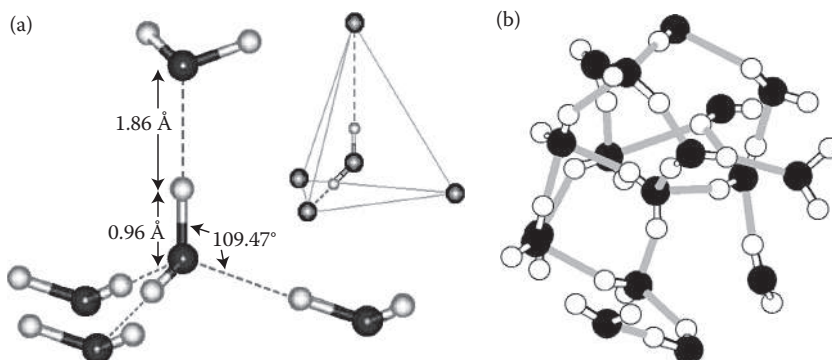


FIGURE 27.1 (a) Hydrogen bonding of water molecules in the tetrahedral configuration. (From A. Chaplin, M. 2008. Water structure and science: www.lsbu.ac.uk/water/index2.html—with permission.) (b) A close-up configuration of liquid water at 298 K, with both four- and three-coordinated molecules. (From B. Finney, J.L. 2004. *Philosophical Transactions of the Royal Society of London B*, 359, 1145–1165. With permission.)

as well as various ring structures (e.g., four-, five-, six-, and even sevenfold), which result from the local defects caused by bond angle and bond length variations, can be found.

The oxygen nuclei is characterized by high electronegativity, therefore the pairs of electrons in the O–H covalent bonds are drawn toward O-atom. As a result, each hydrogen atom is slightly charged positively and the oxygen atom is slightly charged negatively. Due to the asymmetric distribution of electron density between oxygen and hydrogen nuclei, water has polar properties, with a marked electric dipole moment of 1.83 D directed along its axis of symmetry and significant dipole polarizability (Finney, 2004; Housecroft and Sharpe, 2005; Maréchal, 2007). The polarizability of the molecule is centered on the O-atom (1.4146 \AA^3) with only small polarizabilities centered on the H-atoms (0.0836 \AA^3) (Chaplin, 2008). Polarity has an important contribution to the formation of intermolecular attractive forces and, hence, the association of water molecules is through the multiple hydrogen bonding on a three-dimensional basis. The distance between hydrogen and oxygen atoms in a H-bond is about 1.86 \AA . A hydrogen bond is classified as weak interaction with a dissociation energy of about 13–25 kJ/mol; electrostatic forces make the major contribution to this energy (Fennema, 1996; Zaritzky, 2006). However, the existence of the hydrogen bond network results in the 63 anomalous water properties, which are described in detail on the Martin Chaplin web page: www.lsbu.ac.uk/water/index2.html.

27.3 WHY FREEZE?

Water is the major component of almost all food materials (Table 27.1) and greatly influences their texture, appearance, quality, as well as microbial, chemical, and biochemical degradation.

Water in food matrices exists in two states, namely as “non-bound” and “bound.” First, term “non-bound” is related to the freely available solvent water, condensed within the capillary structure or in the cells of a food that behaves physically and chemically as pure water. Second, water fraction is “bound” to polar groups or ionic sites on molecules such as starches, pectins, and proteins, thus becoming less active (Belton, 1997; LeBotlan et al., 1998; Fellows, 2000; Fessas and Schiraldi, 2001, 2005; Choi and Kerr, 2003; Vaclavik and Christian, 2008). The water activity (a_w) is defined as the ratio of the partial vapor pressure above a given substance with respect to the vapor pressure above pure water at the same temperature. The water activity is correlated to the amount of water in the matrix and is often used to characterize the different states of water. Free water is available for microbial, enzymatic, or chemical activity. It has been reported that by decreasing the a_w value, the rate of food deterioration by microorganisms is significantly reduced. Almost all

TABLE 27.1
Water Content Ranges of Commonly Frozen Foods

Food Commodity	Water Content (% Wet Mass Basis)
Breads	28–45
Doughs	5–45
Fish	50–80
Ice cream	59–62
Meats	35–90
Vegetables	55–90
Fruits (strawberries, raspberries)	87–90
Ready meals	50–85

microbial activity is inhibited below $a_w = 0.6$, most fungi are inhibited below $a_w = 0.7$, most yeasts at $a_w < 0.8$ and most bacteria at $a_w < 0.9$. Kinetics of enzymatic reactions is strongly dependent on the ability of substrates to diffuse to the active sites on the interior surface of an enzyme. At low a_w values, mobility of food ingredients is limited, thus enzymatic activity is greatly reduced. Food quality is also affected by occurrence of chemical changes. The most important reactions that are taking place during food storage are Maillard browning and oxidation of lipids. In both cases there is necessity to optimize the content of freely available water, as excessive decreasing of a_w may enhance the rate of reactions (Fellows, 2000). Controlling the water availability in food matrices is essential for maintaining the satisfying physicochemical properties and extension of the storage time. In the food industry, freezing is one of the most common methods utilized to reduce the amount of free water. However, freezing may affect the nutritious value, the taste, and the global quality of food products.

27.4 CONVENTIONAL FREEZING

Freezing of biological material is widely used in the food industry to extend the shelf life of food. The quality of frozen food is closely related to the freezing rate, to the frozen storage conditions (time and temperature), and to the thawing processes.

In the industrial practice, freezing is done with different types of equipment, such as a blast air freezer or brine freezer. Freezing processes consist of two interacting phenomena, namely nucleation and ice crystals growth. During cooling, the temperature can be lowered below the theoretical freezing point. The temperature difference between the product and the expected initial freezing temperature is called the *supercooling*. The supercooled state is thermodynamically unstable and in a considered system, ice nucleation may occur unexpectedly. Metastability is the main reason for which nucleation process is difficult to predict and control. The importance of the nucleation phase comes from the fact that the size of ice crystals in a frozen sample depends on the number of nuclei formed during freezing. Formation of fine and numerous ice crystals minimizes tissue damage, drip losses, and color modifications of frozen foods (Fellows, 1988; Li and Sun, 2002). It is thus very important to control the operating conditions during this phase to obtain good nucleation. The size of ice crystals interacts with the supercooling degree and the rate of freezing. The larger the supercooling, the higher the nucleation rate can be. It is well known that a fast freezing rate tends to form a fine ice structure, while a slow freezing rate leads to large ice crystals (Reid, 1993). Therefore, by lowering the temperature as fast as possible, a higher preservation of the tissue is expected.

It was found that the size of the ice crystals is reversely proportional to the square root of the velocity of the freezing front (Reid, 1980; Chevalier et al., 2000). Chevalier et al. (2000) on the basis

of experimental studies on the freezing of cylindrical gelatin gels, developed the following equation relating the mean diameter of ice crystals \overline{d}_p with the local freezing rate u :

$$\overline{d}_p = a \times u^b \quad (27.1)$$

From the fitting of the experimental results with the power law, the following values of the coefficients were obtained: $a = 2.89 \times 10^{-7} \text{ m}^2/\text{s}$ and $b = 0.45$, with R^2 equal to 0.81. It is worth to note that coefficient a has the same dimension as the diffusion coefficient; by assuming that the constant a is physically linked to the mass diffusivity of water in the matrix, it seems logical that with a higher mass diffusivity of water the ice crystals will be bigger. In literature, freezing rates can be numerically represented in two ways. The first one is the approach by Plank (1941) who defined the freezing rate as the velocity of the phase change front ([dimension]/[time]). It is based on the linear velocity of the phase change front (called LVA). From a practical point of view, an averaged freezing rate can be evaluated by dividing the characteristic dimensions of the product (thickness for the slab, radius for a cylinder or a sphere) by the nominal freezing time (Bøgh-Sørensen, 2006), which is defined as the time that elapsed between 0°C and a temperature 10°C below the initial freezing point. An alternative consists in calculating the cooling velocity during the phase change (Havet et al., 2000). However, great care must be done to select the initial and final temperature. LeBail and Cornier (1994) showed that it is preferable to consider an initial temperature just below the initial freezing point; for example, a final temperature 10°C below the initial freezing point. Such an approach means the cooling rate will be evaluated during the ice crystallization phase.

The amount of freezable water that is frozen can be considered as a criterion to assess the degree of freezing, especially in the case of a complex food made of different phase (i.e., ready-to-eat meal). Based on the definition proposed by the IIF-IIR red book (Bøgh-Sørensen, 2006), the target temperature for which a food can be considered as fully frozen has been defined as the temperature for which 80% of the freezable water is frozen, or −10°C if the percentage of 80% is passed at temperatures higher than −10°C. A case study is proposed by LeBail et al. (2008) with a model food made of two constituents (pie + filling).

The temperature of −18°C (0°F) is usually considered as the best compromise for the storage of food. Even though some food may be stored at higher temperatures such as −10°C, most frozen foods are stored at −18°C or at lower temperatures.

27.5 THEORETICAL ASPECTS OF ELECTROFREEZING

Electrofreezing phenomenon is based on the ability of strong electric field or an electrostatically charged surface to induce nucleation of solid phase in supercooled liquid.

Water molecules are characterized by significant dipole moment and dipole polarizability. The molecular dynamics analysis performed by several authors (Svishchev and Kusalik, 1994; Jung et al., 1999; Shevkunov and Vegiri, 2002; Vegiri, 2004a,b; Zangi and Mark, 2004; Sun et al., 2006) indicates that water molecule dipoles are polarized by the application of external DC electrostatic field. As a result, water molecules align with the direction of the electric field vector and the hydrogen bonds become stronger along the field rather than along orthogonal directions (Shevkunov and Vegiri, 2002; Vegiri, 2004a,b; Wei et al., 2008). On the basis of Monte Carlo calculations, Shevkunov and Vegiri (2002) postulated that under an electric field strength of $1.5 \times 10^7 \text{ V/m}$, water clusters achieve the most aligned state with the dipoles pointing less than 90° to the direction of the field. Sun et al. (2006) also reported that with the increase of the electric field strength from 0 to $8.0 \times 10^9 \text{ V/m}$ at −15°C, liquid water becomes more ordered and similar to ice-like structure. Due to the dipole reorientation, water molecules reach the most stable state, with the maximum value for the Boltzmann distribution function. Thus, application of electrostatic fields can enhance ice nucleation and affect the freezing process. Formation of solidified water or ice, I, under a homogeneous

electric field of magnitude 5.0×10^9 V/m observed by Svishchev and Kusalik (1994) in the process of molecular dynamics simulations. Ice nucleation occurs when the Gibbs free energy of the system reach its minimum value ($\Delta G < 0$). For a linear system, characterized by permanent polarization P , subjected to the electrostatic field E condition, the free energy G_E is defined by

$$G_E = U - TS + pV - [V_C E \cdot (\mathbf{e}_0 \mathbf{e}_r E + P)] \quad (27.2)$$

where V_C is the volume of the system that is subjected to the field, ϵ_r is the relative permittivity of the system and ϵ_0 is the vacuum permittivity (Guggenheim, 1967). The free energy of a spherical nucleus formation in the presence of an electric field can be presented as (Marand et al., 1988; Mullin, 2001):

$$\Delta G_E = 4\pi r^2 \gamma - \frac{4}{3} \pi r^3 (\Delta G_v + PE) \quad (27.3)$$

where r is the radius of the sphere, γ is the surface free energy of the crystal fluid interface, and ΔG_v is the free energy change of the transformation per unit volume. In the case of zero electric field, the Gibbs free energy ΔG_0 is given by

$$\Delta G_0 = 4\pi r^2 \gamma - \frac{4}{3} \pi r^3 \Delta G_v \quad (27.4)$$

From the comparison of Equations 27.3 and 27.4 it follows that structural transformations observed in the system exposed to the external electric field are related with the change of the Gibbs free energy.

Molecular simulations performed by Jung et al. (1999) also revealed that the application of the electric field strength of 5.0×10^9 V/m at -30°C can affect diffusion coefficients of liquid water. In the presence of an electric field, the value of diffusion coefficients ($D_{x,y} = 3.884 \times 10^{-7}$ cm²/s; $D_z = 6.310 \times 10^{-7}$ cm²/s) were reduced to about one-tenth of the value obtained without an electric field (6.833×10^{-6}). Taking into consideration Equation 27.1, it can be presumed that the application of an electrostatic field can also reduce the size of ice crystals due to the decrease of the diffusion coefficient.

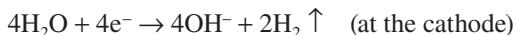
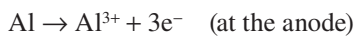
In addition to the above-mentioned approach related to the interaction between an electric field and water molecules, it is interesting to mention that a voltage difference of several 10 V appears in the vicinity of ice crystals between the ice crystals and the solution during freezing of an aqueous solution (Pruppacher et al., 1968). This voltage difference results in a current of 10^{-7} A. The intensity of the current depends on the solution, but does seem to be related to the freezing rate. This phenomenon would be explained by the incorporation of ions in the ice crystal. However, the voltage difference tends to be reduced in the case of low concentration in salts. Between the initial freezing point and around 10°C below this temperature, the surface of ice crystal is covered of a quasi liquid and not ordered layer. The thickness of this layer is of around 40 \AA at -5°C (Fletcher, 1968) and tends to decrease close to the initial freezing temperature. This layer would contain H_3O^+ and OH^- ions which orientation depends on the molecular orientation of molecules contained in this layer. The voltage difference within the crystallization layer has also been observed by Fletcher (1970).

All the above-mentioned phenomena seem to indicate, and would also give credit to, some interaction between electrical disturbance and ice crystallization in biological matrix.

27.6 EXPERIMENTAL STUDIES ON THE ELECTROFREEZING PHENOMENON

Early experimental studies on the influence of external electrical fields on ice nucleation were mostly related to the behavior of water drops in thunderclouds (Wang and Pruppacher, 1980; Martin

et al., 1980). Then research concern was shifted toward the possibility to control ice nucleation in supercooled water by the application of an intense electric field. Various experimental procedures were designed for studying the electrofreezing phenomenon, such as application of direct current between electrodes or exposition of supercooled samples to operation of electrostatic field—alternative (AC) or direct (DC). Shichiri and Nagata (1981) investigated influences of the electrical current, both AC and DC, on the nucleation of ice crystals in supercooled distilled water. The authors observed spontaneous nucleation at an average temperature of -6.4°C on the vessel wall. However when direct current, ranging from 0.1 to 1.0 mA, was applied between two naked electrodes (mounted in a distance of 1.5 cm from each other) immersed in supercooled water, ice nucleation occurred at electrodes at lower degree of supercooling. The application of AC current did not induce any effect. Hozumi et al. (2005) revealed that among other factors, the shape of the electrode end surface plays important role in the electrofreezing process. Authors analyzed electrodes with flat (0.5 mm in diameter) and sharp (0.1 mm in min. and 0.5 mm in max. diameter) tips. In the experimental set-up, electrodes were placed at a distance of $300\text{ }\mu\text{m}$ from each other and an electric charge (50 and 120 V) was applied to the water sample for 90 s at a specified temperature. In case of flat end surface of the anode, nucleation was observed at a lower degree of supercooling. Shichiri and Nagata (1981) performed studies with different kinds of electrodes (Mg, Al, Ti, Zr, Co, Ni, Cu, Ag, Pt, Au) to determine if electrode material has an important impact on the nucleation process. They found that when a little current (up to 0.2 mA) was applied, a rapid increase of nucleation temperature in the case of Al, Ti, Zr, and Pt electrodes occurred. What was characteristic for all investigated electrodes is, that nucleation temperature became constant at higher values of applied current. Differences in supercooling degree had significant effects on ice morphology. At large supercooling, many dendrite crystals grew radially from one electrode toward the vessel wall. However, at a higher nucleation temperature many disc-like crystallites were formed. Moreover, nucleation was affected by the polarity of the electrodes and the ionization tendency of the electrode material. Nucleation occurred at cathodes when electrodes with small ionization tendencies (e.g., Ag, Pt, Au) were used, and on anodes in the case of electrodes with high ionization tendencies (Mg, Al, Ti, Zr). Hozumi et al. (2003) carried out similar investigations regarding the effects of six electrode materials (Al, Cu, Ag, Au, Pt, and C) on the freezing of supercooled, ultra-pure water with applying an electric charge. In their experimental setup, two electrodes were placed at a distance of $300\text{ }\mu\text{m}$ and a whole sample was cooled at the constant rate. When the target temperature was achieved, an electric charge (50 V DC) was applied for 30 s. It was found that the applied electric charge had an effect on freezing. The probability of freezing occurring was strongly dependent on the electrode material and was ordered as follows: $\text{Al} = \text{Cu} > \text{Ag} > \text{Au} > \text{Pt} > \text{C}$. As in the studies of Shichiri and Nagata (1981), nucleation appeared from the anode of the electrode when the ionization tendency of a material was high (Al, Cu). Such behavior is probably due to the melting of the anode material and further formation of the coordination compound. For example, in the case of Al electrodes, reactions occur as follows:



Around formed Al^{3+} , six water molecules are placed and an ion of $[\text{Al}(\text{H}_2\text{O})_6]^{3+}$ is made. In the case of electrodes with low ionization tendency, only a few coordination compounds are formed, because these materials do not melt well. The explanation proposed by Hozumi et al. (2003) is in agreement with observations made by Shichiri and Araki (1986), who examined the structure of electrode (Pt, Ti) surfaces by electron diffraction after experiments. On a Pt cathode, Pt_3O_4 was detected. In the case of a Ti anode several different compounds were found, such as Ti_3O_5 , Ti_4O_7 , Ti_5O_9 , and TiO_2 . Types of formed oxidants depended on the time of current application. Due to the oxidation process occurring during water electrolysis, passivity was made at the surface of an

anode and resulted in material from the electrode that did not melt. As a result, authors noted the suppression of the freezing probability. On the basis of experimental results, Shichiri and Nagata (1981) concluded that the nucleation process is strongly related to the occurrence of electrochemical processes at the electrodes and presumably with the formation of gas (H_2 or O_2) bubbles. To confirm this hypothesis Shichiri and Araki (1986) performed experiments in which two electrodes covered with the Teflon tube were attached to a bubble of visible size. To induce ice crystallization, authors applied direct current (DC), alternative current (AC), and an electrostatic field. The obtained results showed that, after application of the DC voltage nucleation occurred at the moment when the bubble was detached from the electrode and the electrode surface was in contact with the supercooled water. However, alternative current (60 Hz) and an electrostatic field hardly affected the nucleation.

All aforementioned research on electrofreezing (EF) was related with ultra-pure or distilled water. Petersen et al. (2006a,b) analyzed the potential of a high electric field to induce ice nucleation in distilled water and in aqueous solutions with added nonionic compounds such as 10% (w/v) of hydroxyethylstarch (HES), glucose, sucrose, mannitol, and 5% (w/v) of glycine. Experiments were performed with two types of electrode setups for direct and indirect nucleation. In the first case, gold wire with a 0.5 mm diameter inside an insulating polyethylene tube (0.6 mm outer diameter) was introduced into the sample. Isolation by the PTFE-tube prevented the current flow through the sample and thus minimized the occurrence of electrolytic processes. In order to increase the field strength at the tip, the electrode had a beveled edge. In this experimental setup, ice nucleation was induced directly inside the sample. For indirect EF nucleation, the ice nucleus was formed at platinum electrodes in a separate volume of pure water (100 μ L) and then grew through a very narrow cannula and Teflon tube into the sample. The cannula and Teflon tube act as a diffusion barrier between cap and sample volume, ensuring this way that ice nucleation is independent on the sample composition. With the described electrode caps, authors developed a multi-sample freezing block with eight freezing units shown in Figure 27.2.

Investigated samples were cooled at the rate of 1 K/min and ice nucleation was induced by the application of high-voltage pulses (4 kV) for 2.5 ms at specified temperatures: -1.5°C , -4.5°C , -8.5°C , and -16.2°C , while spontaneous samples froze in a range between -11.5°C and -17.1°C . In both types of experimental setups, controlled ice nucleation was observed with very high reproducibility. In the case of the HES solution, only one experiment out of 32 was not successful due to problems with the electrode. Scanning electron microscopy analysis (Figure 27.3) revealed a strong relationship between temperature nucleation (T_n) and obtained texture of frozen material. HES samples nucleated at low T_n had sponge-like texture with small closed pores, however, structures of frozen samples at a high T_n were characterized by large, lamellar-oriented pores. Crystallization at -8.5°C resulted in formation of a mixed structure of plate- and sphere-like pores.

Besides nonionic additives Petersen et al. (2006a) also studied the influence of NaCl addition on EF nucleation. The highest concentration of added sodium chloride was 0.8 mmol/L, which is in a range of the salt content of tap water and is about 20 times less than in the physiological solution (150 mmol/L). Yet this small quantity of NaCl showed strong inhibitive influences on the process of direct EF nucleation and resulted in a decrease of T_n . Also, with the increase of ionic concentration, induced ice nucleation via application of high voltage became less reproducible. In the case of ionic additive, authors successfully applied experimental setup for indirect EF nucleation, where the freezing process was not depending on the sample composition.

Lipids are another important food component and due to their wide range of chemical composition it is difficult to control their crystallization. Yan et al. (1997) investigated the effect of electrofreezing on heat and mass transfer during crystallization of dielectric butter. The sample was composed of six fatty acids and had typical polymorphic properties. The melting temperature of the sample was 35°C . During the experiments, the temperature of the cooling source was kept at 15°C and 15 kV was applied to the rod electrode placed inside the butter. The comparison of obtained cooling curves with and without application of high voltage revealed that the crystallization process was accelerated due to the enhanced heat and mass transfer from the crystal surface to the bulk melt

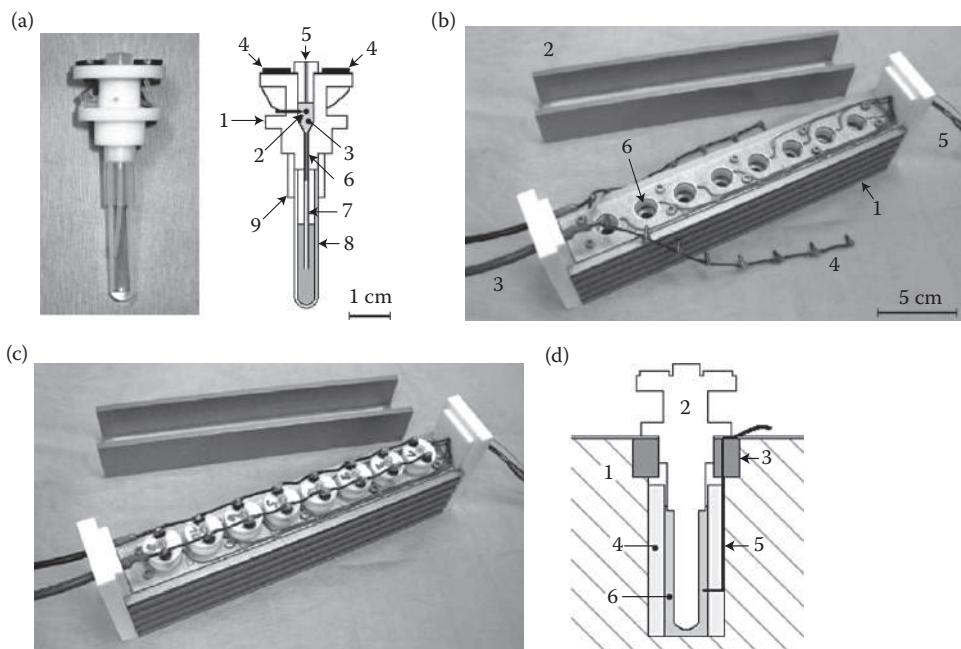


FIGURE 27.2 Experimental setup: (a) One out of eight sample units (samples attached to electrode caps) composed of the PTFE housing (1), the two platinum electrodes (2), reaching into pure water (3), the electrical receptacles (4), the silicone plug (5), to press water through the narrow cannula (6), and the PTFE tube (7), and the sample container (8), connected by a silicone tube (9) to the electrode cap. (b) Freezing block consisting of anodized aluminum block (1), the cover (2), the HV-pulse feeding (3), the electrical plugs for the electrode caps (4), thermocouples for temperature measurement (5), and the boreholes with PTFE damping rings (6). (c) Freezing block with mounted and electrically connected sample units. (d) schematic drawing of a cross-section of the freezing block: aluminum block (1), contour of electrode cap and sample (2), PTFE clamping ring to fix electrode cap (3), aluminum sleeve (4), to fix the thermocouple, which measures temperature in the gap between block and sample (5) and 1-propanol used to improve heat conductance. (From *Cryobiology*, 53, Petersen, A. et al., A new approach for freezing of aqueous solutions under active control of the nucleation temperature, 248–257, Copyright 2006a, with permission from Elsevier.)

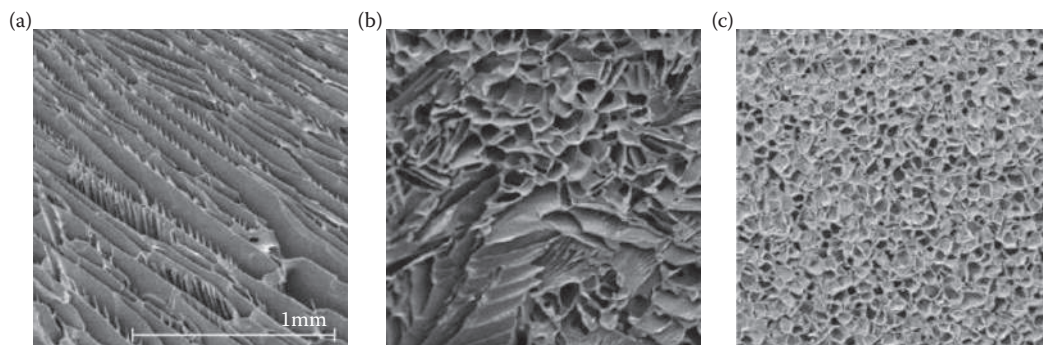


FIGURE 27.3 Scanning electron microscopy images of hydroxyethylstarch samples nucleated at different temperatures: (a) $T_N = -1.5^\circ\text{C}$, (b) $T_N = -8.5^\circ\text{C}$, (c) $T_N = -16.2^\circ\text{C}$, via application of 4 kV for 2.5 ms. All images were taken at the same magnification. (With kind permission from Springer Science+Business Media: *Heat Mass Transfer*, Reduction of primary freeze-drying time by electric field induced ice nucleus formation, 42, 2006b, 929–938, Petersen, A., Rau, G., and Glasmacher, B.)

under electric field condition. Additional DSC analysis of butter sample treated with 15 kV showed that the application of high voltage resulted in the formation of very stable crystals as compared with the untreated one.

Bernemann et al. (2006) and Spindler et al. (2008) studied the applicability of electrofreezing in cryopreservation of different cells (CD34+ stem cells isolated from human cord blood, human keratinocytes, murine fibroblasts, and human endothelial cells). The cooling rate and nucleation temperature are known as the most important factors, which play a crucial role in formation of extracellular ice, followed by dehydration and, hence, cell survival of the biological materials. Thus, the possibility of the initiation of ice nucleation at a desired temperature is of great practical importance. In both studies the same experimental setup for indirect EF nucleation developed by Petersen et al. (2006a, b) was used (Figure 27.2). Due to the application of 3 kV between platinum electrodes it was possible to control and optimize the nucleation process and, hence, relative CD34+ cell survival achieved 90% (Bernemann et al., 2006). In case of keratinocytes, the decrease of nucleation temperature from -4°C to -10°C resulted in an increase of cell survival from $85 \pm 5\%$ to $93 \pm 2\%$. Similarly, a linear increase in cell survival with the nucleation temperature a decrease for fibroblasts and endothelial cells was observed (Spindler et al., 2008).

It can be observed that, so far, research on electrofreezing was mainly related to the ice nucleation induced by the electrical charge. From the theoretical approach, it follows that the application of an electrostatic field should affect water properties and enhance formation of more ordered ice-like structures. Shichiri and Nagata (1981) and Shichiri and Araki (1986) applied an electrostatic field in a range from 0 to 1.0×10^6 V/m to the water samples and although the latter value was relatively high, authors did not observe any effects. This is contrary to the recent results obtained by Wei et al. (2008) and Orlowska et al. (2009). In both cases were developed original experimental setups in which water samples were placed between parallel plate electrodes without getting into contact with the electrode material (Figure 27.4). Thus, the occurrence of electrolytic processes was entirely eliminated.

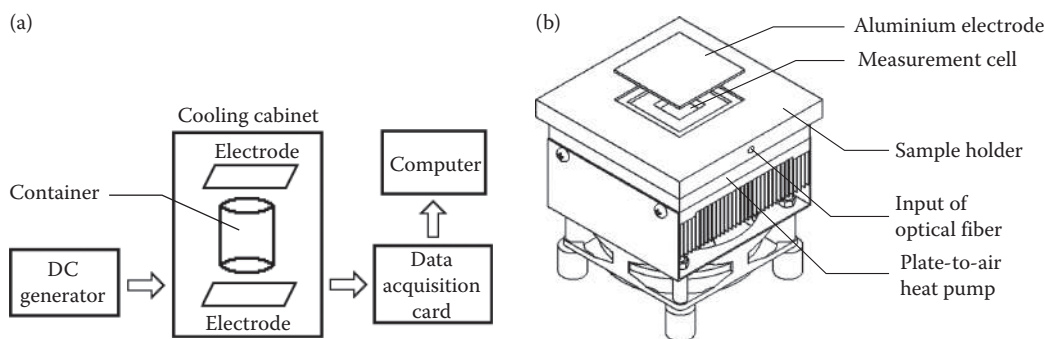


FIGURE 27.4 Schematic diagrams of the experimental systems used by: (a) Wei et al. (2008): 1 mL of distilled water was placed in a tetrafluoroethylene container between two copperplate electrodes situated in a distance of 20 mm from each other. The temperature inside the cooling cabinet was set at constant temperature of -30°C and during the cooling process the temperature of the sample was automatically recorded at intervals of 1 s by the temperature sensor placed inside the sample container. (From *Cryobiology*, 56, Wei, S., Xiaobin, X., Hong, Z., and Chuanxiang, X., Effects of dipole polarization of water molecules on ice formation under an electrostatic field, 93–99, Copyright 2008, with permission from Elsevier.) (b) Orlowska et al. (2009): 1.6 mL of distilled water was placed in the measurement cell assembled on a heating–cooling system. Metal plate of the heat pump MPA100 served as a ground electrode and the upper aluminum electrode was placed 2 mm above the surface of the sample. Temperature was registered every second by the Datalog acquisition system connected with the Luxtron optical fiber installed inside of the measurement cell. (From *Food Research International*, 42, Orlowska, M., Havet, M., and LeBail, A., Controlled ice nucleation under high voltage DC electrostatic field conditions, 879–884, Copyright 2009, with permission from Elsevier.)

In the experiments performed by Wei et al. (2008), 1 mL of distilled water was subjected to the DC electrostatic field condition in a range from 0 to 1.0×10^5 V/m. Authors noted that with the increase of the strength of an applied electrostatic field, a decrease was observed in supercooling degree and an increase in the phase transition time. Spontaneous ice nucleation appeared at $-7.27 \pm 0.56^\circ\text{C}$ and solidification time was 714 ± 64 s. Application of the 1.0×10^3 V/m did not affect the water crystallization process. However, under an electrostatic field strength of 1.0×10^5 V/m, ice nucleation was initiated at $-5.68 \pm 0.36^\circ\text{C}$ and the phase transition time was extended to 829 ± 36 s. Authors correlated the prolonged time of crystallization with the decreased degree of supercooling, rather than with the action of the electrostatic field. Wei et al. (2008) drew such a conclusion based on the two types of experiments performed under 1.0×10^5 V/m in an electric field condition. In the first type of measurements, high-voltage supply was turned off immediately after the occurrence of ice nucleation. In this case, the nucleation temperature was $-5.37 \pm 0.57^\circ\text{C}$, and the phase transformation time was 850.3 ± 41.40 s. In the second set of tests, high voltage was continuously applied through the whole duration of the experiment, and the recorded nucleation temperature and solidification time were $-5.52 \pm 0.46^\circ\text{C}$, and 834 ± 29.29 s, respectively. Recently, similar observations was reported by Orlowska et al. (2009), who applied DC high voltage during cooling of distilled water (1.6 mL) from 1°C to -16°C . Experiments were conducted at selected electrostatic field conditions: 0 kV, 1.0×10^6 V/m, 2.5×10^6 V/m, 5.0×10^6 V/m and 6.0×10^6 V/m. In Figure 27.5 are shown typical cooling curves obtained at 0 kV, 2.5×10^6 and 5.0×10^6 V/m and in Table 27.2 are presented results. In case of nontreated samples, spontaneous ice nucleation occurred at $-12.28 \pm 2.19^\circ\text{C}$ and solidification time was 303 ± 43 s. Obtained results also revealed positive correlations between the electrostatic field, nucleation temperature, and crystallization time. The application of 1.0×10^6 V/m caused an increase in both: in the nucleation temperature to $-9.16 \pm 0.72^\circ\text{C}$ and in the phase transition time to 350 ± 17 s. However, under the highest electrostatic field strength condition, that is, 6.0×10^6 V/m, ice nucleation appeared at $-5.90 \pm 1.39^\circ\text{C}$ and crystallization time was 393 ± 24 s. The modification of the crystallization time may be caused by the amount of refrigeration energy stored during the supercooling. During the rupture of the supercooling, a heat balance is made within the solution that can be considered in adiabatic condition. Some ice is thus formed (sensible heat stored between initial freezing temperature and temperature of the rupture of the supercooling is equal to the mass of ice multiplied by the water–ice latent heat), resulting in a reduction of the

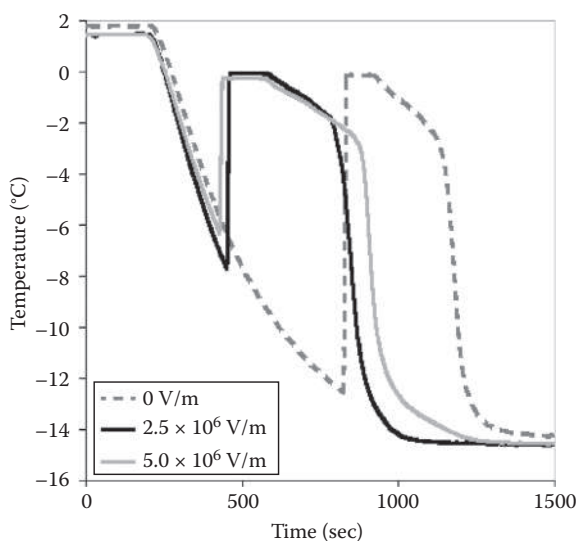


FIGURE 27.5 Cooling curves obtained under different electrostatic field conditions.

TABLE 27.2

Average Values of the Nucleation Temperature (T_N) and Crystallization Time (t_c) Together with Their Standard Deviations under Different Electrostatic Field Conditions

Electrostatic Field (V/m)	T_N (°C)	t_c (s)	Temperature			
			−3°C	−4°C	−5°C	−6°C
0	−12.28 ± 2.19	303 ± 43	—	—	—	—
1.0 × 10 ⁶	−9.16 ± 0.72	350 ± 17	—	—	—	—
2.5 × 10 ⁶	−7.36 ± 1.13	371 ± 21	—	—	0%	50%
5.0 × 10 ⁶	−6.64 ± 0.95	403 ± 32	—	33%	83%	100%
6.0 × 10 ⁶	−5.90 ± 1.39	393 ± 24	0%	100%	—	—

Source: From *Food Research International*, 42, Orlowska, M., Havet, M., and LeBail, A., Controlled ice nucleation under high voltage DC electrostatic field conditions, 879–884, Copyright 2009, with permission from Elsevier.

Note: In the right part of the table is given percent of successfully induced ice nucleation via the application of HVEF for 30 s at specified experimental conditions.

freezing plateau duration with increasing amplitude of the supercooling. Therefore, the higher the supercooling, the lower the duration of the plateau at freezing temperature.

Experimental results obtained by Wei et al. (2008) and Orlowska et al. (2009) are in good agreement with the theoretical studies on the influence of an electrostatic field on water properties. The biggest discrepancy between experimental and theoretical approach comes from the fact that water crystallization can be induced at the electrostatic fields of 2–3 orders lower than it was envisaged on the basis of results from computer simulation analysis (Svishchev and Kusalik 1994; Jung et al., 1999; Sun et al., 2006). Water molecules exposed to the external electrostatic field are polarized and consequently aligned in the direction of electrostatic field lines. This leads to the rearrangement of a hydrogen bond network and the formation of more ordered ice-like structures. Changes induced in the water structure via the application of HVEF affect the Gibbs free energy and enhance nucleation of the solid phase. Experimental studies confirmed the conclusion made by Vegiri (2004a), on the basis of theoretical investigations, that the increase of the field strength acts along the same direction as the temperature decrease.

Orlowska et al. (2009) also made attempts to induce ice nucleation at a desired supercooling degree by the application of DC high voltage for 30 s. In these experiments the following conditions were used: −6°C under 5 kV; −6°C, −5°C and −4°C under 10 kV; −4°C and −3°C under 12 kV. As it can be seen in Table 27.2, the choice of an appropriate supercooling and electrostatic field condition may result in the formation of ice nuclei with very high probability. It is also worth noticing that by increasing the electrostatic field strength, it is possible to induce controlled ice nucleation at a lower supercooling degree. The possibility to control the process of ice nucleation, which has stochastic character, is of great practical importance. The application of this method in the industrial practice may result in a reduction of process time and an improved and more uniform quality.

27.7 FREEZING UNDER COMBINED ELECTROSTATIC AND MAGNETIC FIELDS CONDITION

Owada (2007) invented a freezing apparatus containing the means for simultaneous application of an oscillating electric field of variable frequency in the range of 50 Hz to 5 MHz and/or a uniform static (from 1 to 10⁴ Gauss) or variable (from 1 to 10³ Gauss) magnetic field to foodstuffs. Owada discovered that under combined electrostatic and magnetic field conditions the content of free water in the food matrix was reduced due to the formation of hydrates with proteins and carbohydrates. As a result, nucleation of ice crystals was prevented and a high supercooling degree was achieved. Quality

tests have been conducted on raw meat and fishery products (e.g., chicken, tuna) frozen under such conditions. It was observed that after three months of frozen storage, and subsequent thawing under running water at 10°C, a significant enhancement of the quality of food was obtained in comparison with control. Treatment under combined electrostatic and magnetic fields resulted in prevention of cell destruction, reduction of the drip amount, and preservation of the initial color, flavor, and taste as the original raw food, in all studied products. The same positive effects are reported in another recent Japanese patent (PCT/JP2007/000845) of a hybrid freezer, where food products are subjected to the simultaneous operation of a magnetic field, electromagnetic wave, and cold wind.

27.8 ELECTROTHAWING

Thawing of frozen foods requires special attention to prevent undesirable changes in foods, such as drip losses, microbial growth, loss of water-soluble nutrients, and discoloration (Fellows, 2000; Maroulis and Saravacos, 2003). Conventional thawing methods, such as exposing frozen food to warmed air and flowing water or high-speed thawing with an electric heating or high-frequency wave source, cause temperature increases of the frozen food to unexpected high values. Temperature changes result in food deterioration and propagation of various germs. Considering all aforementioned problems, development of new thawing methods, which minimize thawing time, avoid overheating, and excessive dehydration of the food, are of a high interest. Ohtsuki (1991) invented a process for rapid food thawing at low temperatures (in a range from -3°C to 3°C) by applying negative electrons induced by the high-voltage electrostatic method. Applying this innovative method to frozen tuna meat, beef, and eggs, resulted in a decrease of the thawing time to 1/4–1/3, in comparison to the conventional process carried under the same temperature condition in a refrigerator. Moreover, electrostatic thawing (ET) did not cause food discoloration or fading, which was more effective in sterilization, and dripping was also not observed (Ohtsuki, 1991). Similar observations were made by Ito (2002), who thawed meat (roast beef, sirloin, chicken) and seafood (scallop, shrimp, sole, tuna, crab) products under alternating voltage conditions in an invented thawing apparatus. More susceptible to the cell damage during freezing–thawing processes are products of plant origin, due to higher water content within the tissues. In the case of frozen carrots, Fuchigami et al. (1994) reported that the application of ET significantly accelerated defrosting, preventing cell damage and drip from the tissues as well as preserving the quality of the thawed carrot disks.

27.9 IMPROVEMENT OF FOODS SHELF-LIFE BY HVEF PRETREATMENT

Storage of fruits and vegetables that preserve their freshness, color, mechanical properties and good quality still constitute a big challenge. The most important factors that affect the shelf-life of a fruit are: storage temperature, relative humidity, air circulation, and gas composition as well as respiration kinetics, which enhance biochemical processes that lead to quality deterioration. As the fruit ripens, respiration increases and it begins to soften. At a certain point in maturity, some fruit will go through a concentrated burst of increased ethylene and respiration, referred to as the *climacteric*. From that point the fruit is ripe and will reach senescence and soften very rapidly (Atungulu et al., 2004). Modification of the storage conditions, for example, by lowering the temperature and controlling the gas composition, can reduce the respiration kinetics and thus improve the shelf-life. However, reduced temperature and increased relative humidity along with controlled CO₂ and O₂, need sophisticated technology at a high cost (Ratti et al., 1996; Atungulu et al., 2003; Bajgai et al., 2006; Palanimuthu et al., 2009).

Several studies have reported the potential of high-voltage electrostatic field (HVEF) treatment of foods and vegetables prior to storage in controlling the respiration rate (RRCO₂) and, as a result, enhancing the shelf life without affecting the food quality. Treatment of lettuce, spinach, and komatsuna (a Japanese type of spinach) with alternating current (AC) and direct current (DC) HVEF caused a decrease in RRCO₂. The effect was found to be directly proportional to the voltage applied

and the time of exposure (Bajgai et al., 2006). Kharel et al. (1996) applied 430 kV/m to sweet peppers (*Capsicum annuum* L.), pears (*Pyrus pyrifolia* Nakai var. culta Naki), “Karari” plums (*Prunus salicina* Lindl.), bananas (*Musa* AAA cv. Cavendish subgroup) and apples (*Malus domestica* Borkh). Authors noted that freshness and the shelf life of sweet peppers were improved by keeping the greenness and reducing the physiological loss of mass. In the case of pears, plums, and bananas, reduction in $RRCO_2$ was observed during the climacteric period and for apples during the post-climacteric period. Atungulu et al. (2003, 2004) applied a direct current (DC) electric field to a parallel plate electrode system and a multiple ($n = 11$) needle-type negative corona discharge electrode system in order to study HVEF effects on Fuji, Rome Beauty, Golden Delicious, and Starking Delicious apple varieties. Treated apples were then stored at 0°C, 10°C, and 23°C at 75% relative humidity (RH). Intermittent and continuous electric field treatments resulted in retardation of respiration and suppression of climacteric peak in fruits. The total color difference and soluble sugar concentration changes were lower in treated samples and treated apple tissues were also tougher and stiffer than the untreated ones. Atungulu et al. (2005) used same experimental setup to study HVEF effects on plums (*Prunus salicina* Lindl, c.v. Ooishi and Sodom) and apples (*Malus domestica* Borkh, c.v. Fuji), before and after ripening. For the pre-ripe fruits, weight loss was suppressed and the Brix percentage increased due to treatment. The pH value increased in the control (14%) whereas in the treated samples, the value remained unchanged for the same period of storage. In the case of post-ripe treatment, the Brix percentage decreased with storage time and the change from the initial value was highest in the control samples for the same period of storage. Continuous electric field treatment in corona discharge at 10 kV of Fuji at 20°C resulted in a suppression of decay and mold growth. Similar observations were made for plums continuously treated in a corona discharge field of 40 kV. Partial if not complete retardation of microbial activity of both fungi and bacteria as well as suppression of $RRCO_2$ in treated (2, 5, or 8 kV cm^{-1} for 30, 60, or 120 min) cranberries (*Vaccinium macrocarpon* Aiton) was noted by Palanimuthu et al. (2009). Bajgai et al. (2006) applied AC and DC HVEF of field strength 430 kV/m for 2 h to emblic fruits (*Phyllanthus emblica* L.), and as a result color value, rotting, and vitamin C content were superior in AC HVEF treated fruits compared to untreated ones. Treatment of Wase Satsuma mandarin fruits (*Citrus unshiu* Marc. and *C. unshiu* Marc. var. praecox Tanaka) with alternating current (AC) HVEF of 10⁵ kV/m for 1 h caused a delay in chlorophyll degradation (Bajgai et al., 2006). Shivashankara et al. (2004) analyzed the HVEF treatment on greenhouse-grown tree ripe (TR) and mature green (MG) mangoes (cv. Irwin) before 20 and 30 days of storage at 5°C. Electric field pretreatment affected the respiration and antioxidant capacity of TR fruits and did not have any significant affect on other parameters (i.e., titratable acidity, firmness, total soluble solids, total phenol, total carotenes content, peel color) compared with untreated samples. Wang et al. (2008) applied a negative electric field (−2 kV for 2 h at 20°C) to green mature tomatoes. In treated samples the authors observed a reduction in $RRCO_2$, delaying the decline of firmness, the change in color, total soluble sugar, and titratable acidity during storage. The effect of HVEF treatment was also studied in the case of seeds from “Sunny” lettuce (*Lactuca sativa* L.), Tsumamina (*Brassica campestris* L.) and “Tokinashi,” “Kaiware” radish (*Raphanus sativus* L.), and also varieties of rice. AC electric fields of more than 50 kV/m promoted the early growth of Tsumamina, Tokinashi, and Kaiware radish and both the AC and DC HVEF stimulated the germination rate of “Sunny” lettuce. DC positive and negative HVEF strengths were investigated as promotive and inhibitory on the germination of seeds depending on the field strength, treatment time, and electric capacity (Bajgai et al., 2006).

27.10 REFRIGERATION UNDER HVEF CONDITIONS

A device for refrigerating under applied alternating voltage conditions has been invented by Ito (2002). This equipment has shown high usefulness for the prolonged storage life of food products. Various fruits (strawberry, grape) and vegetables (both noncut and cut: cucumber, carrot, leek, broccoli, asparagus, celery) treated with high voltage (0.5, 1, 2, and 3 kV) at −2°C, −1°C, 0°C, and 1°C,

maintained freshness without browning and drying for a significantly longer time as compared with traditional method of refrigerating. Similarly, prolonged freshness was achieved in the case of meat (roast beef, sirloin, chicken) and seafood (scallop, shrimp, tuna, oyster) products. Recently, Hsieh and Ko (2008) studied the influence of applied DC HVEF (10^5 V/m) on fresh carrot juice properties and the shelf life during its refrigeration at $4^\circ\text{C} \pm 1^\circ\text{C}$ for 12 days. The authors have shown that the combined treatment resulted in better preservation of the physicochemical and nutritional properties of juice in comparison with common refrigeration. Treated with a high-voltage electrostatic field, carrot juice had better stability in the turbidity, color difference, total carotenoids, total phenolics, and tannins. Application of HVEF also significantly lowered microbial growth and, hence, the storage quality of treated carrot juice was improved.

27.11 CONCLUSION

Assurance of the food safety as well as food preservation issues are major issues and drive the scientific research on the innovative methods of food processing. This chapter presented literature on the potential of refrigeration under electric field conditions. It was shown that storage, freezing, and thawing processes of various food products with HVEF treatment has beneficial effects on the maintenance of nutritional and quality values as well as the prolongation of shelf life. Most of the research studies focused on the water properties under electrostatic field conditions, as water constitutes one of the major food components and greatly affect food quality. Theoretical and experimental studies revealed that the water molecule is reoriented in the presence of an external electric field due to its polar properties. This is related with the gaining of the most stable state with the maximum value for the Boltzmann distribution function and decreasing in the Gibbs free energy. These are the main factors affecting supercooling degree and freezing processes. Morphology of ice crystals and the resulting preservation of the cell properties of biological materials are strongly dependent on the supercooling degree and heat and mass transfer conditions. Thanks to the decreasing of the nucleation temperature as well as the possibility of controlled ice nucleation at a desired temperature, it is possible to affect the texture of frozen products and also save energy. It is also worth noticing that at higher voltages, corona discharge can occur and as a result ozone can be formed. Refrigeration under such conditions can inhibit microbial spoilage and increase the storage life of food products.

Application of high-voltage electrostatic fields in food processing and preservation is a relatively new scientific domain. Further research is necessary in order to reveal the effect of an external electric field alone or in combination with a magnetic field on the heat and mass transfer and on the freezing and thawing processes as well as on the chemical constituents of different foods.

ABBREVIATIONS

AC	alternating current
DC	direct current
ET	electrostatic thawing
EF	electrostatic field
HVEF	high-voltage electrostatic field
RH	relative humidity
RRCO ₂	respiration rate

NOMENCLATURE

a	coefficient (m^2/s)
b	coefficient
d_p	mean representative ice crystal diameter (m)

$D_{x,y}$	diffusion coefficient of the x and y directions (m^2/s)
D_z	diffusion coefficient of the z direction (m^2/s)
E	electrostatic field (V/m)
p	pressure (Pa)
P	permanent polarization (C/m^2)
r	radius of the nuclei (m)
S	entropy (J/K)
T	temperature (K)
t_c	crystallization time (s)
T_N	nucleation temperature (K)
U	inner energy (J)
u	local freezing rate (m/s)
V	volume (m^3)
V_c	volume of the system subjected to electrostatic field (m^3)
ϵ_0	vacuum permittivity, $\epsilon_0 = 8.854187817 \times 10^{-12} (\text{A}^2\text{s}^4\text{kg}^{-1}\text{m}^{-3})$
ϵ_r	relative permittivity of the system
γ	surface free energy of the crystal fluid interface (J/m^2)
ΔG	Gibbs free energy (J)
ΔG_0	free energy of the system without applied electrostatic field (J)
ΔG_E	free energy of the system with applied electrostatic field (J)
ΔG_v	free energy of melting per unit volume (J/m^3)

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Section 9

Process Validation

28 Validation of Ohmic Processing Systems

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28.1 INTRODUCTION

Ohmic systems, their designs, operation, and pros and cons have been described in the preceding chapters of this book. In this chapter information is presented in a decision-making format that should be useful to those involved with the setup of an aseptic processing or ultra-high-temperature (UHT) processing system that uses Ohmic heater(s) for heating the product. It is important to note that regulatory requirements (food safety) are based on the type of product(s) to be processed rather

than the type of system used to process the food, although the regulatory authorities concerned may have some additional requirements for specific systems. Although these requirements may affect purchase decisions, it is understood here that a decision to use Ohmic heating has been made and is being implemented. However, the reader is urged to get familiar with the pertinent regulations that may be referred to, but will not be detailed, in this chapter. In addition, it is assumed that the Ohmic system is simply a heating system and no additional microbial effect as a result of passage of current is claimed.

A complete processing system will consist of supplementary and ancillary equipment that forms the overall system. Although the system is designed around Ohmic heating, conventional heat exchangers will be included in it. Perhaps for functional reasons a conventional heat exchanger may be used for pre-heating the food. Certainly conventional heat exchangers will be used to cool the product(s) to their filling temperature, whatever that may be. Everything from the pre-processing storage vessels to secondary packaging equipment and warehouse racking systems must be addressed at some point in time. Although none of these decisions can be ignored, the scope of this chapter is limited to equipment used to pump, sterilize, cool, and deliver product(s) to the filler.

Before discussing specific validations, some of the underlying concepts for a successful operation should be explored. One major concept is that, systems using Ohmic heating are continuous flow processes. Thus, the performance of one equipment component may affect the performance of the entire system. When considering the resulting quality of the finished product, the operator should not view the equipment as individual components to be linked together, but as an entire system.

As an example, consider a pre-heater that has inadequate heating capacity for the volume or product to be processed. This may create an unbalance in the Ohmic heater, resulting in excess power usage or simply inadequate heating, thereby violating the heating requirement for the product in question. By increasing the temperature of the heating medium in the pre-heater(s), it may be possible to achieve the proper final temperature before the product enters the hold tube. However, this increase will result in a higher temperature differential (ΔT) between the product and the heating medium. This higher ΔT (depending on the product) may result in an increased rate of fouling of heat exchange surfaces, thus reducing the overall heat-transfer efficiency of the unit. Excess fouling can also result in flavor changes in the product, excessive pressure within the processing unit, a loss of energy efficiency (increased steam demand), and difficulty in cleaning, which compounds the problem later on. Additionally, if regeneration is used, maximum efficiency will not be obtained if the heat exchange surface is not adequate.

Commercial operations being what they are, a business and operators prefer systems that can be used to process products ranging from juices to low-acid foods containing large particles. Flexibility comes at a cost; the cost being the ability to operate efficiently for any specific product type. Ohmic systems will typically require more complex process controls than a conventional aseptic or UHT systems with the exception of possibly steam infusion systems, which are quite complex. However, with the current day programmable logic controllers (PLC) and inexpensive computing power, controlling an Ohmic system is much easier than it used to be when it was first introduced.

It is also important to remember that it can typically take longer than often predicted to install and “debug” systems consisting of Ohmic heating. Therefore, it is necessary to allow sufficient time for testing and validation before scheduling commercial production. Success will often depend on the effort and expense of trained, qualified operators and quality control personnel. The skill of these people will make the difference between success and failure. Trained system operators who know what to do and why it must be done correctly are absolutely essential to keep equipment running smoothly. Selecting and training the right personnel is one of the most important steps in the establishment of a successful operation; however, it is often ignored.

28.2 PRODUCT STERILIZATION EQUIPMENT

28.2.1 THE INFLUENCE OF THE PRODUCT ON EQUIPMENT SELECTION

Before making equipment decisions, the operator should first define the characteristics of the product to be produced. Since one goal of continuous processing is to optimize product quality, equipment purchased (including all components of the system, from feed pumps to the materials which compose the final package) should be tailored to the needs of the product. As a rule, the choice of Ohmic heating is virtually always on the assumption that foods containing particles will be processed in the system; if only homogeneous products are to be processed, conventional heat exchangers would be the primary choice.

Another consideration in the selection of equipment is the level of thermal treatment required by the product. One of the most important product considerations to define is the pH. Generally, low-acid foods ($\text{pH} > 4.6$) require a greater heat treatment in order to attain commercial sterility, than do acid or acidified food products. The fact that the processing requirements are different for high-acid than for low-acid products may simplify equipment needs. Food products with a $\text{pH} \leq 4.6$ require a less severe heat treatment than low-acid foods; therefore, the demand for heat exchange capacity will be less for acid or acidified foods than for low-acid foods. Thus, some savings can be achieved by not spending money for unnecessary equipment. However, an installation specifically designed for high-acid foods may not be suitable for the processing of low-acid foods.

Equipment used for processing low-acid foods must be designed to operate at 270–300°F (132–149°C). Back pressure (overpressure in excess of the vapor pressure of the product at processing temperatures) must be provided in the system to operate at the necessary process temperatures. The system overpressure should be at least 10 psi (0.7 bar) over the vapor pressure of the product at the highest temperature in the system in order to prevent flashing.

Other product characteristics, including viscosity, particle size, and type of particulate matter, if present, should also be defined, as these will dictate the design and capacity of equipment needed.

28.2.2 DETERMINING AND CONTROLLING THE PRODUCT FLOW RATE

As described in previous chapters, thermal inactivation of microorganisms within a food product is an integral of time and temperature. Therefore, a thermal process for a particular product will include time and temperature requirements. The conventional approach to assuring proper time at the specified temperature involves the use of a “hold tube” within the system immediately following the product heaters. The term is a misnomer, since product does not remain stationary but continues to flow through the entire system including the hold tube. The size of the hold tube is designed to retain the fastest particle of product for a specified time at a controlled flow rate. Therefore, if the temperature of the product at the end of the hold tube is at or above the minimum specified in the process and the flow rate has not exceeded the specified maximum, then every element of homogeneous food will receive at least the minimum thermal process. However, in the case of foods containing large particles ($>1/8$ inch or 3 mm), the fluid temperature at the end of the hold tube may not be a sufficient critical control factor. The residence time distribution of particles will be a deciding factor if it turns out that the heating rate of the particle interior is slower than the fluid heating rate. Measurement of residence time distribution of particle-containing foods was reviewed by Ramaswamy et al. (1995) and the reader is encouraged to review this publication before embarking on continuous processing of foods containing particles.

Certain characteristics are essential to a specified thermal process. The product supply throughout the system must be steady and the flow rate must be controlled. Thus, an appropriate device must be included to regulate product flow through the hold tube. This is usually accomplished by positive displacement, progressive cavity, or a reciprocating pump, designated as the timing or metering pump. The design and selection of the timing pump is especially critical for foods containing particles.

This pump can be either fixed rate or variable speed. If the pump is variable speed, a means must be provided to prevent unauthorized speed changes so that the maximum product feed rate is not exceeded. Centrifugal pumps should generally not be used as timing pumps because they are not positive displacement pumps and the flow rate will be affected by system pressure unless they are supplemented by a reliable, calibrated flow meter tied to critical factor control in the system PLC code.

A means must also be developed to verify the specified product flow rate with instruments in the form of various flow measuring devices, which give a direct indication of flow, that are commercially and readily available. This is also a major challenge for foods containing particles, as flow meters cannot be depended on for confirming any particular particle-to-liquid ratio. Theoretically, a mass flow meter could be adapted, if properly calibrated and programmed, to provide a sense of average ratio of particles to fluid. However, it would be product formulation specific and complex if the food contains a variety of different particles. The regulatory agencies have accepted flow meters, as long as adequate data to verify accuracy and reliability of such instruments is available before these instruments are used to satisfy regulatory requirements for flow rate documentation.

28.2.3 MONITORS AND CONTROLS

To verify that all critical factors are met and the equipment is functioning as intended, adequate instrumentation, recorders, and controls must be in place. Particular attention should be paid to the location of sensors and to the controlling logic. In case of foods containing particles, there may have to be a specialized incoming particle size distribution quality control program to ensure that maximum particle size restrictions are met. In addition, due to the nature of Ohmic heating, formulation control (as it affects electrical conductivity of the particles and liquid) may be very strict.

As previously noted, the temperature of every particle of the product must be at or above a specific temperature for a specified time. Achieving the proper hold time depends on proper sizing of the hold tube (to be discussed later), flow rate of the product, and product formulation if the food contains discrete particles. For homogeneous products, temperature can be documented by indicating and recording devices properly located in the hold tube. The temperature at the inlet of the tube is monitored with a temperature recorder-controller located at the final heater outlet. An acceptable temperature-indicating device must be installed between the hold tube outlet and the inlet to the first cooler. In addition, there must also be an automatic recording device located in the product stream at the hold tube outlet. The product temperature measured at the hold tube outlet represents the minimum product temperature within the hold tube. The temperature-recording device chart graduations must not exceed 2°F (1°C) within a range of 10°F (6°C) of the desired product sterilization temperature.

The operator should keep in mind that the temperature-indicating device is considered the reference temperature instrument by the regulatory agencies. The temperature recorder must be adjusted to agree as nearly as possible with, but not higher than, the known accurate temperature-indicating device. The temperature-indicating device must be tested for accuracy against a known accurate standard thermometer upon installation and at least once a year thereafter, or more frequently, if necessary; in the United States it is every quarter. The testing is done by the local dairy inspector to ensure its accuracy for Grade A dairy products.

If regeneration is used, the pressure of the sterile product must always be higher than the pressure of the raw product. One pressure sensor is typically located at the sterile product outlet and the other at the raw product inlet of the heat exchange unit. A differential pressure or the individual pressures of raw and sterile product must be recorded continuously. Other requirements and recommendations regarding temperature monitoring and recording devices are contained in the pertinent regulations discussed elsewhere. Those who will be in charge of these functions should become familiar with the appropriate regulatory requirements.

Temperature monitoring equipment, as well as pressure sensors, timers, and so on, will typically be interfaced with various control systems. Control systems available for both processing and

packaging equipment can be adapted for complete automation. However, this adaptation may not necessarily mean that these installations will meet regulatory requirements or that the operation is being properly controlled. The logic controlling such systems must be evaluated to verify that adequate controls, interlocks, and other safety features have been incorporated and are functioning as intended. The control software and system performance should be verified at installation and routinely thereafter. The interlocks (alarms) that monitor critical functions must be tested periodically to prove that they are functioning properly. The results of these challenges are recorded as part of the system validation procedure. Changes to the control software should only be made by authorized personnel, following a written change control policy for the plant/factory.

Recent regulatory changes do allow exclusive use of automatic control systems in the United States (this was always permitted outside the United States) to assure commercial sterility, but require verification of the automatic control system including but not limited to, installation qualification, operational qualification, and critical instrument, and calibration. Regulators also look for some operator intervention in the form of handwritten records and operator interaction with the control system. Automatic controls systems and possibly paperless recording may become essential in the case of complex systems and products. Thus, appropriate gauges and recording devices should also be included so that operators can observe results and record the information in the daily production log. This precaution will also serve as a check against the automatic system itself. Further recommendations regarding automatic control systems can be found in NFPA's bulleting 43-L "Automatic Control Guidelines for Aseptic Systems Manufacturers and Companies Using Aseptic Processing and Packaging for Preserving Foods."

28.3 PROCESSING SYSTEM STERILIZATION

As required by regulatory agencies, all product contact surfaces downstream from the final product heater must be brought to a condition of commercial sterility prior to production. Most systems use pressurized hot water (or saturated steam in some cases) to sterilize the processing system. The system is sterilized by maintaining the temperature within all parts of the sterile side of the system at or above a specified temperature by continuously circulating the sterilizing medium for a specified period of time. If steam is used as a sterilizing medium, adequate provisions must be made to remove condensate from the system. Inadequate sterilization can result from condensate collecting in low spots within the system since such condensate build-up could result in low temperatures.

Aseptic systems may include unique items such as aseptic pumps, flash tanks, and surge tanks in addition to heat exchanger, piping, fittings, and valves. Due to the large capacity of various surge tanks, these units are usually sterilized with saturated steam rather than hot water. Surge tank sterilization may proceed separately from the sterilization cycle for the rest of the processing system but should occur simultaneously with this cycle if possible. The surge tank may require special attention, such as documentation of uniform heat distribution during sterilization. Microbiological challenges may also be needed to confirm sterility of inaccessible areas associated with the surge tank where temperatures can be directly measured.

The pre-production equipment sterilization cycle is usually monitored by temperature sensors located at the coldest point(s) within the system. The sterilization time should incorporate only that portion of the cycle when all temperatures are at or above the established minimum temperature. If the temperature drops below the minimum sterilization temperature, the timer should be reset to zero and timing should not start until the proper temperature is reestablished. A permanent and continuous record of temperatures must be made during the sterilization period.

28.4 MAINTENANCE OF STERILITY

After the system sterilization cycle is completed, a transition phase is initiated during which the system beyond the end of the hold tube is cooled and readied for the introduction of product.

From the end of sterilization through the end of the production period, the system must be maintained in a sterile condition; prevention of potential recontamination is a must. One of the most common ways to prevent contaminants from entering the system is to maintain the product under constant positive pressure. A back pressure device located after the product coolers and typically before the filler is used to maintain the product at a pressure which is usually 10–15 psi (~1 bar) over the pressure exerted by the product at its maximum temperature. This excess pressure not only prevents flashing of the product but also assists in preventing product recontamination after sterilization. That portion of the system between the back pressure valve and product filler should also be maintained under a positive pressure, which is appropriate for the filler being used.

There are usually areas where rotating shafts (aseptic pumps) or reciprocating shafts (valve stems) may enter an aseptic system in the sterile product area. An effective barrier against the entry of microorganisms has to be provided at all potential contamination sites. Steam seals are commonly used for this purpose. Steam seals consist of an area where steam in a groove or trace in the housing forms a ring around a pump shaft or covers the total stroke of a valve stem. Steam must be continually supplied to the seal area, and the proper operation of the steam seal must be verified by the operator periodically, or better yet, continuously monitored with a temperature sensor tied into the PLC. Operator verification usually consists of visually checking for steam discharge from the individual seal or an indication of temperature at seal discharge points. Another alternative is to use pressurized sterile condensate barriers, which are static barriers by design as opposed to steam seals that are active barriers. In both cases, the barriers themselves must be pre-sterilized when the system is pre-sterilized.

An automatic flow diversion device may also be utilized in an aseptic processing system to prevent potentially nonsterile product from reaching the packaging equipment. The flow diversion device, usually located after the back pressure valve, must be designed so that it can be adequately sterilized and operated in a reliable manner. It is recommended that the flow diversion device be activated by the control system, which monitors temperature at the end of the hold tube and other devices that monitor critical factors such as differential pressures in a regenerator or positive pressure in a surge tank. Should there be a deviation in, or failure of, any of these critical factors, the flow diversion device should divert product flow away from the filler and prevent product from being packaged.

28.5 ESTABLISHING THE SCHEDULED PROCESS

For those companies manufacturing shelf-stable, low-acid foods, the regulatory agencies (in the United States) require registration of processing plants and the filing of thermal processes and sterilization procedures before product can be manufactured and distributed. Regulatory agencies rely upon aseptic processing and packaging authorities to establish adequate parameters for sterilization of product, packages, and equipment so that the commercial sterility of each container of the end product is assured. The time/temperature combinations required to render the product commercially sterile, along with the list of factors critical to achieve and maintain sterility in the processing and packaging systems, is referred to as the scheduled process and must be filed with the appropriate regulatory agency. The scheduled process should be obtained in writing from a process authority and kept on file by the processor.

To design a time–temperature process sufficient to provide a commercially sterile product and establish a scheduled process, the thermal resistance of specific spoilage organisms and/or organisms of potential public health significance found in the food is considered. Other items such as product flow rate, product formulation, flow characteristics of the product as it passes through the hold tube, and the system design and operation must also be considered by the process authority.

28.5.1 IDENTIFICATION OF CRITICAL FACTORS

The list of critical factors will include any item, identified by the process authority, which must be controlled and monitored in order to assure that the product produced is commercially sterile. The selection and quantification of critical factors, to be part of the scheduled process, begins during the initial equipment design review and continues through the testing and start-up period. During the design review, potential critical factors are identified, instrumentation and control functions are reviewed, and regulatory compliance is evaluated. Particular attention should be paid to the monitoring and control equipment and protocols associated with each of the potential critical factors.

Once the equipment is installed, testing should be conducted to verify proper operation. This testing may modify the list of potential critical factors identified during the pre-installation review. This work begins with testing of the pre-production sterilization cycle to assure that all product contact surfaces are sterilized properly. As part of this testing, temperature monitoring and control points are established and the sequence of sterilization operations is finalized.

The number of critical factors associated with a particular operation will be increased by including such options as aseptic surge tanks in the system. For example, a critical control point associated with the use of aseptic surge tanks is that the tank be maintained under a positive pressure at all times the tank is considered sterile. This is accomplished by supplying sterile air or other gas to the tank. Depending on the method used to sterilize the air, various critical factors will be associated with the air supply system. If the air is sterilized by incineration, a minimum temperature may be specified at the discharge of the incinerator. If bacteriological filters are used, a replacement and/or sterilization frequency may be specified in the scheduled process. These factors would be considered critical to the successful production of aseptic product.

Examples of other critical factors that may be included in a scheduled process are:

- Time and temperature of equipment presterilization cycle
- Maintenance of a minimum pressure differential within regenerative heat exchangers
- Product flow rates
- Product formulation
- Time and temperature of product sterilization

Critical factors will also be identified for packaging equipment, and these will be part of the scheduled process as well. Identification of these factors will be discussed in the section on packaging equipment.

Violation of any critical factor constitutes a process deviation. Product involved in a deviation should not be packaged, but if it is, it must be placed on hold pending review of the production records by a process authority.

28.5.2 CALCULATING THE THERMAL PROCESS

The factors needed to establish that the food product received a time–temperature (thermal) process adequate to render that product commercially sterile are:

- The resistance of potential spoilage organisms
- Product feed rate
- Flow or rheological properties (flow characteristics) of the food as it passes through the hold tube
- Hold tube dimensions

The heat resistance of potential spoilage organisms is determined through established procedures (Stumbo, 1973) and is quantified in terms of the number of minutes at a reference temperature

(usually 250°F or 121°C), which would be required to inactivate a specific microbial population. This number is referred to as the “ F ” value, sterilizing value, or target lethality value. The thermal process must be designed so that every particle of product will receive heat equivalent to or greater than this target lethality (F) value.

To calculate the exact times and temperatures needed, the inactivation rate of the target microorganisms versus temperature must also be determined in the specific product. This rate constant, termed the “ z ” value, is the number of degrees required for the thermal resistance to change by one order of magnitude. By convention, $z = 18^\circ\text{F}$ (10°C) is used most often for process calculation or evaluation purposes for low-acid foods.

A term commonly used to describe a target commercial sterility value is F_0 . F_0 is the lethality in minutes at a temperature of 250°F (121°C) to inactivate a target microbial population which has an inactivation rate (z) of 18°F ($F_0 = F_{250}^{18}$).

Identifying the “ F ” value and knowing the z value of the target microorganisms allows the process authority to calculate a time at any temperature to inactivate the same number of spoilage organisms. By using the formulas below, it can be shown that a thermal process of 280°F (138°C) for 7.8 s is equivalent in terms of the destruction of microorganisms present in the food to 6 min at 250°F (121°C) ($F_0 = 6$). When referring to an aseptic process, the time specified by the process authority at a specific temperature is the minimum resident time and minimum temperature for that product.

Once the minimum residence time and temperature necessary for a product to achieve commercial sterility have been calculated, the process authority must determine the dimensions of the hold tube which will yield the minimum residence time for the fastest moving particle of food so that every particle will achieve at least the desired commercial sterility (F) value.

The product residence time in the hold tube is a function of the hold tube length, inner diameter, feed rate, and flow behavior of the product. Within the hold tube, individual product elements will flow at different speeds depending on the rheological properties and formulation of the food. This is complicated by the presence of discrete particles, if any, in the product formulation. Generally speaking, the more viscous the product, the greater will be the resistance to flow along the walls of the tube. Thus, the product closer to the wall will flow more slowly and, since feed rate is constant, the product in the center of the tube must flow more quickly. Therefore, some knowledge of the properties of the food is needed to predict the residence time for the fastest moving product elements. Testing may be necessary to determine these properties in order to establish minimum residence times for various products and hold tube configurations.

The hold time of the fastest element of the food is determined from the velocity of the fastest moving particle as follows:

$$t = L/V_{\max} \quad (28.1)$$

where t = time in seconds (s), V_{\max} = velocity of fastest moving particle, and L = the length of the hold tube. The velocity of the fastest moving particle depends on the velocity distribution within the hold tube.

Various authors have reported models of flow behavior for foods, whether they are Newtonian or non-Newtonian (Casson, 1959; Bird et al., 1960; Rao, 1977; Charm, 1978; Nakayama et al., 1980; Rao and Anantheswaran, 1982; and Dervisoglu and Kokini, 1986). The flow behavior models can be used for computing the maximum velocity in a pipe. For laminar flow of Newtonian fluids, the maximum velocity is twice the average velocity, that is,

$$V_{\max}/V_{\text{avg}} = 2 \quad (28.2)$$

and

$$V_{\text{avg}} = Q/A \quad (28.3)$$

where Q = flow rate and A = cross section area. When the flow is turbulent, the velocity ratio ranges from 1.2 to 2 (McCabe and Smith, 1976).

Palmer and Jones (1976) compared the holding times computed for Newtonian and non-Newtonian (Power Law) foods in laminar and turbulent flow. They indicated that holding time computed with the assumption that the food was Newtonian in laminar flow would be conservative unless the food was dilatant in laminar flow. However, dilatant foods are rare, if not nonexistent (Rao, 1977, M.A. Rao, 1985, personal communication). Thus, the hold time can be calculated from Equation 28.1 once the velocity of the fastest moving particle is estimated on the basis of the fluid flow model that fits the particular food in question.

However, the situation becomes much more complicated for non-Newtonian foods containing discrete particles. The residence time distribution of particles cannot be predicted by simple models unless one wants to use a very conservative estimate in Equation 28.2. This often leads to over-processing and resulting quality loss in the product. Thus, experimental determination of residence time distribution is the only practical approach. Various approaches are discussed in Ramaswamy et al. (1995). A statistically valid experimental design is required and is dependent on the distribution model used to fit the experimental data. A distribution free statistical approach may be possible, however, this should be considered carefully in consultation with the local regulatory agencies; what may be acceptable in the United Kingdom may not be acceptable in the United States or vice versa. In some cases, as in California, the state regulatory group must also be consulted as they review the process design independently of the US FDA.

Once a maximum residence time is established, a process temperature for homogeneous fluids can then be calculated using the following:

$$T = T_R + z \log (F/t) \quad (28.4)$$

where T = process temperature measured at the end of the hold tube, T_R = reference temperature, z = temperature change necessary for the D -value to change by a factor of 10, t = hold time calculated from V_{\max} and F is the sterilizing value needed at T_R to achieve commercial sterility for the product.

In the case of foods containing particles, some kind of procedure must be developed to estimate the temperature in the interior of the thermally most remote part of a particle. This would be a function of the dimension of the particle, the thermophysical properties of the particle and its speed through the various parts of the heating section. In general, it cannot be said that the largest particle is the one to track since it may not be the fastest particle through the system. A competent process authority with appropriate skill at modeling heat transfer should be consulted for this type of process development.

28.5.3 PROCESS CONFIRMATION

Once the hold tube length, process temperature, and product flow rate have been calculated and the system has successfully completed trial runs, inoculated packs of product or simulated product should be conducted for confirmation of proper system operation. These inoculated packs are conducted by batch inoculating product with an appropriate test organism followed by processing at the maximum flow rate (minimum residence time) specified in the scheduled thermal process. Temperatures are varied during the inoculated pack to yield product processed to pre-selected lethality values. Generally, five temperatures are used and the pack is run continuously, starting with the highest temperature and then adjusting the temperature downward to the next target temperature.

At least 100 packages containing inoculated product should be collected from each temperature interval. These packages are incubated at the optimum temperature for the growth of the test micro-organism and monitored for spoilage. Results of the inoculated pack should correlate with calculated lethality delivered by the system at each temperature and should confirm operation of the equipment.

For foods containing particles, it is necessary to develop a method to inoculate the particles with the test microorganism. These particles have to be properly distributed into the exact product formulation and processed through the system. For an Ohmic system the electrical conductivity is a critical factor and the particles should mimic actual food particles in the formulation in size, shape, material, and electrical conductivity. A means must be developed to capture these particles in packages and, as above, they should be incubated at the optimum temperature for the growth of the test microorganism.

As mentioned before, the local regulatory authority should be consulted before embarking on such testing to ensure that the data collected will be acceptable.

The automatic controls and safety devices built into both the processing and packaging systems should also be challenged to verify proper function. For example, the flow diversion device should be challenged to verify that no product is packaged following a temperature drop or other fault (including electrical conductivity of particles and fluid). Other interlocks, such as system shutdown in the event of a loss of sterile air pressure, or loss of proper pressure differentials, should also be verified. Agreement between sensing devices, indicators, and recorders should be checked, and the programming of automatic control devices should be verified. Calibration of all sensing and measuring devices must be completed before system start up and at subsequent intervals as prescribed by regulations.

It is suggested that at least four small-scale production runs of un-inoculated product be processed and packaged and incubated followed by 100% examination for evidence of spoilage. Records of these commissioning trials, as well as other test results, should be retained by the packet.

28.6 ASEPTIC PACKAGING SYSTEMS

Aseptic systems are unique in many ways. One characteristic which sets this type of thermal processing operation apart from most others is the need to document process adequacy for the product, the aseptic surge tank (if any), the adequacy of the sterilization process for packages, and adequacy of the sterilization process for filling and packaging equipment. Therefore, the scheduled process must also address those factors which are critical to achieving and maintaining sterility within the packages and packaging equipment. The identification of these critical factors will be discussed below. First, however, we will review various classifications of packaging equipment.

28.6.1 SYSTEM DESCRIPTIONS

Aseptic packaging units are designed to fill sterile product into a sterile package and close and seal the package in a sterile environment. These systems must be able to accomplish at least the following:

1. Create and maintain a sterile environment in which the package and product can be brought together.
2. Sterilize any filters that will be used to create sterile air that will be used to maintain sterility in the aseptic zone.
3. Sterilize the product contact surface of the package and lid (if any).
4. Sterilize the outside surfaces of the package and lid (if any) that will enter the sterile zone of the filler.
5. Aseptically fill sterile product into a sterilized package.
6. Produce hermetically sealed containers.
7. Monitor, control, and record critical factors.

Since there are a number of ways to satisfy these requirements, there is a substantial variety of equipment available. The following discussion will concentrate on those requirements common to all aseptic packaging systems, using the features mentioned above as a basis for discussion.

Sterilization agents are used in aseptic packaging units to sterilize the packaging material and the internal equipment surfaces to create a sterile packaging environment. In general, these agents involve heat, chemicals, high-energy radiation, or a combination of these. For aseptic packaging equipment, the sterilization agents used must provide the same degree of microbiological safety that traditional sterilization systems provide for canned foods. This rule applies to both the food contact surface of the packaging material and the internal machine surfaces, which constitute the aseptic or sterile zone. The effectiveness of these agents must be proven through extensive biological testing. Equipment that has been thoroughly tested and proven will be accepted or approved by regulatory agencies for packaging commercially sterile low-acid foods in hermetically sealed containers.

The aseptic zone is the area within the aseptic packaging machine, which is sterilized and maintained in a sterile condition during production. This zone provides an environment where the sterile package and product can be brought together, the package filled, and hermetically sealed. The aseptic zone begins at the point where the packaging material is sterilized or where pre-sterilized packaging material is introduced into the machine. The zone ends after the package is sealed and the finished package exits the sterile area. All areas between these two points are considered part of the aseptic zone.

Prior to production, the aseptic zone within the machine must be brought to a condition of commercial sterility. This area may contain a variety of surfaces including moving parts composed of different materials. The sterilant(s) must be uniformly effective throughout the entire aseptic zone. Once the aseptic zone has been sterilized, it must be kept sterile during production. Mechanisms must be provided to allow sterile packaging materials to enter and hermetically sealed finished packages to leave the aseptic zone without compromising the sterility of the aseptic zone.

A wide variety of aseptic packaging systems are in use today. These are easily categorized by package type as follows:

1. Preformed rigid and semi-rigid containers, including:
 - a. Metal containers
 - b. Composite containers
 - c. Plastic cups and bottles
 - d. Drums
 - e. Glass containers
2. Web-fed paperboard laminates and plastic containers
3. Partially formed laminated paper containers
4. Thermoform-fill-seal containers
5. Preformed bags
6. Blow molded containers
7. Form-fill plastic pouches

These are a number of different packaging systems represented in these categories. Not all of these systems, however, are being used for aseptic low-acid food applications because not all of these systems have been proven effective through appropriate testing. Those considering purchase or use of specific aseptic equipment should become familiar with its regulatory status.

28.6.2 CRITICAL FACTORS

As with aseptic processing equipment, the identification of those factors critical to the assurance of commercial sterility for packaging equipment should begin during the pre-purchase review. Identification of critical factors is usually a joint effort by the equipment manufacturer, processors, and the process authority. The equipment manufacturer provides information on the overall design, performance of the system and individual components, instrumentation, and controls; the processor contributes the production requirements, and the process authority provides specific knowledge

concerning sterilization systems and their control. The process authority will identify and establish numerical minimum or maximum limits for the appropriate critical factors associated with each phase of equipment operation.

Currently, packaging equipment used for low-acid foods employs either hydrogen peroxide with heat, peroxyacetic acid based sterilants with heat, ionizing radiation, or heat alone to sterilize the aseptic zone and/or the packaging materials. Research has shown that the sporicidal effect of hydrogen peroxide is greatly enhanced as temperatures are increased (Ito et al., 1973); a similar effect is seen with peroxyacetic acid based sterilants also. Thus, aseptic equipment that uses chemicals such as peroxide for sterilization generally uses heat as well. Therefore, the critical factors applicable to sterilization of the packaging equipment and packaging material usually include chemical consumption rate, concentration, contact time as well as temperature. If heat alone is used to sterilize the aseptic zone, filler and/or packaging material, temperature and exposure time will be included in the list of critical factors. Once critical factors are identified, specific minimum and/or maximum limits will be assigned. For example, a minimum hydrogen peroxide spray temperature may be a critical factor for sterilization of the aseptic zone, or a maximum packaging material feed rate may be a critical factor for container sterilization.

When hydrogen peroxide alone, or as a component of the sterilant, is used, it must be ensured that the residual hydrogen peroxide in the package does not exceed 0.5 parts per million. This maximum allowable residual is universally accepted with the exception of Japan, where it has to be at a nondetectable level.

These critical factors define the specific machine conditions for the biological sterility testing which follows. As testing proceeds, these factors or the specific values may be modified on the basis of test results.

28.6.3 BIOLOGICAL TESTING

For filling and packaging equipment, the testing to be conducted will depend on the sterilization agent or agents to be used and the type of products to be packaged. As noted earlier, a variety of media may be used to achieve commercial sterility in aseptic packaging systems. Different methods of sterilization may be used in different areas of the packaging equipment (i.e., the filler versus the aseptic zone) and for the packaging material itself. The test microorganism may differ for the different sterilants since the organism most resistant to one type of sterilant is not necessarily the most resistant to another type of sterilant (Denny et al., 1979). In choosing the appropriate test organisms for a low-acid aseptic system, it is first necessary to establish the resistance of *Clostridium botulinum* spores or other organisms of public health significance relative to the sterilant(s) to be used. This step should be done with a number of types and strains of organisms since variability in resistance can be expected. Next, nontoxic microorganisms with resistance equal to or greater than that of the most resistant public-health-significant organism must be found to use for in-plant testing. The test organisms we have found to be most useful for various sterilants are shown in Table 28.1 (Denny et al., 1979; Bernard, 1983; Bernard et al., 1986).

In choosing test organisms for an aseptic system for processing and packaging aseptic foods, the processor should also give consideration to potential spoilage organisms such as yeast, lactobacilli, and molds. Again, a number of strains should be tested to select a resistant organism for in-plant tests.

Prior to doing in-plant testing with the chosen microorganism(s), it is necessary to “calibrate” or determine the resistance, of the specific suspension of spores or cells to be used, to the sterilant, since this may vary from culture to culture.

The next step is to challenge the packaging system with the test organism(s). It is assumed that contaminating organisms will be in a dry condition. Thus, dried microorganisms are used for the tests. For testing the pre-production sterilization cycle of the aseptic zone inside the packaging equipment, the organisms may be inoculated directly onto areas in the aseptic zone or, more

TABLE 28.1
Test Microorganisms for Aseptic Systems

Sterilization Medium	Microorganism
Superheated steam	<i>Bacillus stearothermophilus</i> , <i>B. polymyxa</i>
Dry heat	<i>B. stearothermophilus</i>
H ₂ O ₂ + heat	<i>B. subtilis</i> , <i>B. subtilis</i> var globigii, <i>B. licheniformis</i> , or <i>B. stearothermophilus</i>
H ₂ O ₂ + U.V.	<i>B. subtilis</i> , <i>B. subtilis</i> var globigii
Heat of formation	<i>B. stearothermophilus</i>
Gamma or electron beam radiation	<i>B. pumilus</i>
Peroxyacetic acid + H ₂ O ₂ + acetic acid	<i>B. cereus</i> , <i>B. subtilis</i>
Wet heat	<i>Clostridium sporogenes</i> , <i>B. stearothermophilus</i>

conveniently, inoculated onto metal discs or foil strips and allowed to dry. Metal discs may be custom made from a stainless steel sheet or may be cut from the tinplate of metal cans. Such discs are attached to the equipment using wires. Since it may be difficult to find attachment points for wires in the aseptic zone, it is usually more convenient to dry test organisms on stainless-steel foil or aluminum strips and attach these with tape (Aubry, 1983). Strips consisting of 5 mil aluminum foil and metalized tape with a high-temperature adhesive have been used. These are taped to plastic strips until the time of use and may be autoclaved prior to use.

28.7 ASEPTIC PACKAGE INTEGRITY

28.7.1 INTRODUCTION

The objectives of package integrity testing during manufacturing are twofold. First, to eliminate known defects, and second, to provide a reasonable expectation that, no serious defects will reach consumers. Quality control methods rely mainly upon statistical sampling to select samples for destructive testing and visual inspection. The speed of most production lines also dictates that visual inspection is conducted upon statistical samples. A reliable, statistically valid sampling plan is paramount to the ability of most food packaging operations in order to prevent release of defective packages. In the United States, this requirement is contained in Title 21 of the Code of Federal Regulations, part 113.60(a). Regulations vary depending on the geographical location of the production plant/factory. When packaging any shelf-stable low-acid food product in hermetically sealed containers, the packer is required by government regulations to examine container seals with sufficient frequency to assure the hermetic quality of packages being produced.

For packers of items regulated by the USDA, the Food Safety and Inspection Service (FSIS) has outlined its expectations for package testing in the “Guidelines for aseptic processing and packaging system in meat and poultry plants.” The agency states “The establishment must propose appropriate procedures and descriptions to ensure that each individual container is free from defects before shipping.”

For traditional types of containers, such as glass jars and metal cans, the numbers and types of examinations that should be made are well established. The measurements and tolerances that indicate acceptability of seams or seals for these types of containers have been developed over the years and are now integral to quality control programs. The same approach is being used for aseptic containers in developing test methodology for package assessment.

The types of aseptic containers being used and considered for use are a very heterogeneous group. Therefore, in a limited text, it is not possible to review testing procedures for each individual container. However, US FDA’s Bacteriological Analytical Manual describes some methods that are good guidelines (BAM). The attributes of a seal, which make it acceptable to a particular package

or product, are left to the equipment supplier and to the food processor. Ultimately, a good seal is one that is adequate to protect the product inside from spoilage by entry of microorganisms, thus maintaining the container's hermetic nature. A bad seal, conversely, is one which will fail to do so. We should keep in mind that a seal which has a defect is not necessarily a defective seal.

Many suppliers of packaging materials for aseptic filling equipment, also provide the machinery used in package closure. Often the packer is prohibited from using materials from other suppliers by contract. Under these terms the suppliers are responsible for developing and communicating technology required for operating within an acceptable range with minimal package defects.

When technical difficulties arise during production the food packer should first seek to determine if the cause is in one of three areas:

1. Operator or procedural error
2. Machine out of adjustment
3. Material out of specification

Procedures for sampling and testing of packages should be contained in a binder. Official documents are serially numbered, dated, and signed by knowledgeable professionals. Procedures for calibration, testing, and interpretation of test results must be followed with precision allowing for no deviations or shortcuts.

Machine set points and troubleshooting guidelines should also be contained in a binder. All controls, sensors, and indicators on machinery should be clearly identified. Circuits for sensors and controls should be inspected and devices calibrated by authorized persons, prior to use in manufacturing. Unauthorized adjustments to sensors and controls which affect calibrations are forbidden.

Machinability (appropriate flexibility, etc.) of packaging materials should be established by laboratory test procedures and not by trial and error. Standards for receipt inspection by the packer and test methods should be provided by the supplier to enable the packer to identify lots which may be defective or which lack characteristics desired to assure efficient filling and sealing. Materials failing receipt inspection or lacking abilities to perform efficiently during filling and sealing should be set aside and held for investigation. The supplier shall at a later date determine the acceptability of the material.

28.7.2 PRE-PRODUCTION INSPECTION

Pre-production inspection requirements for aseptic packaging material or packages have been developed by the Flexible Packaging Integrity Group of the National Food Processors Association and published in NFPA Bulletin 41-L Flexible Package Integrity Bulletin.

Packaging material should also be checked for obvious defects such as pinholes and for uneven sealing surfaces. If the packaging material sealing surfaces are not smooth and even, an irregular seal may be made which is inherently weaker than a seal which is uniform.

Early in the process of establishing the aseptic operation, special storage requirements for packaging material must be planned for. If the moisture content of paper changes excessively due to improper storage, it may lose some flexibility and cracking (resulting in spoilage) may occur. Packaging material should be stored separately in a temperature and possibly humidity-controlled areas. If other materials, such as oils or chemicals, are stored in the same area, the packaging material may absorb volatiles, which will impart off flavors to the finished product. Packaging material should also be protected from contamination by air and moisture-borne contaminants.

28.7.3 BASE MATERIAL QUALITY

All base materials, such as paperboard, foil, polyethylene, polypropylene, and other plastic films used in the manufacture of flexible or semi-rigid packages to be packed with food for human

consumption, and which come in contact with food packed therein, must be in compliance with applicable FDA regulations or the regulations of other appropriate agencies. All confirmations, checks, and inspections should be conducted according to established manufacturer procedures.

Guidelines for conducting such inspections are contained in NFPA Bulletin 41-L, “Flexible Package Integrity Bulletin.”

28.8 HOLD FOR INVESTIGATION (HFI) PROCEDURES

Materials that do not conform to specified standards for dimensions, materials, and performance characteristics should be placed on-hold and a red tag affixed in a visible area. Use of a RED TAG should indicate that, unauthorized use of these materials could result in the production of unacceptable products.

Hold For Investigation (HFI) Procedures (adapted from NFPA Bulletin 41-L, “Flexible Package Integrity Bulletin”)

1. *Action for Specification Deviations*—An HFI of the affected lot of material or packages is required when the sampling reveals one or more deviations from specifications.
2. *Determination of HFI Quantity*—All affected lots must be held. Prior manufactured material of packages must be examined to establish the point at which the defect started occurring.
3. *Determination of Disposition of HFI Packages*—Disposition of held material or packages will be determined based on a further evaluation to establish if the defective lot will perform its intended purpose. If it is determined that, because of the defect, the material or package will fail to perform its intended purpose, it should be established whether or not sorting or reworking can effectively differentiate between defective and normal material or packages in the held lot. If sorting or reworking can effectively differentiate between defective and normal material or packages, reconditioned the held lot by eliminating the defective units.

28.9 PACKAGING MACHINERY

The general condition of the packaging equipment, as well as the cleanliness and the tensioning and leveling adjustments of the sealing jaws or heads should also be checked. If the sealing device becomes dirty, embossed seals due to soil build-up may result. This problem can cause the plastic material located in the embossed area to be squeezed out of the seal, resulting in a weakened seal. Additionally, if sealing jaws or heads are allowed to slip during the sealing process or if the pressure which is exerted on the packaging material is not great enough or evenly distributed, poorly bonded or weakened seals may result. If these conditions are severe enough, there will be no fusion in part of the seal area.

28.10 SAMPLING PROCEDURES

Requirements in FDA regulations state that sample(s) from each closure device shall be inspected at every start up and not less (frequently) than every four hours of continuous operation. Prudent operators of aseptic equipment sample far more often, than the regulations require. When nonconforming packages are detected, sampling and testing should be done with less time between intervals. With new operations, destructive testing at each start up and every 30 min during operations is common.

The purpose of sampling is to identify the presence or absence of defects affecting hermetic integrity as well as those that affect appearance. More frequent sampling results in fewer packages being filled and sealed that might contain defects. Because packaged products are valuable, the risk

of incurring a loss is reduced when inspection is frequent. If few incidents of defective packages are found, the amount of sampling can be reduced with no significant additional risk incurred.

28.10.1 PRODUCTION LINE INSPECTIONS: VISUAL

Experience has shown that a critical element in producing aseptic product is the packaging machine operator. An experienced operator who is knowledgeable about the equipment and the characteristics of the package and packaging material is essential in minimizing package-related problems.

Inspections on the production line should include both visual and teardown examinations. The operator or other qualified person should visually examine packages for defects, which may affect the quality or integrity of the finished package. Such defects include embossed areas in seals (discussed above), irregular seal width, and scorching. High sealing temperatures resulting in scorched material on the package exterior may occur when line speeds are increased. This higher temperature can weaken the packaging material. Scorching should be considered an indication of a potential problem.

Another defect, which can be detected on the visual exam, is blistering caused by product if the seal area which heats and expands during sealing creates a void. Another problem to watch for is lack of fusion. A lack of fusion at seals can occur due to a variety of problems, including a sealing temperature that is too low.

For web-fed packaging equipment that uses roll stock, which is supplied pre-creased, checking to see that the material is indexed properly is particularly important. If the paper is not folded on the pre-formed creases, not only will the design be off, but there will be a possibility of cracking at the corners.

Visually detectable defects have been classified in terms of public health significance by the Flexible Packaging Integrity Group of the NFPA and published in photo-chart form by the Association of Official Analytical Chemists and its recommended reading. These defects are further defined in NFPA Bulletin 41-L.

28.10.2 PROCEDURES FOR VISUAL INSPECTION OF ASEPTIC PACKAGES

Test methods for plastic and composite food packages are described in the *Bacteriological Analytical Manual* 8th ed. (BAM) and NFPA Bulletin 41-L, "Flexible Package Integrity Bulletin." A preliminary visual examination should precede destructive testing of each sample package. The visual exam will include observation for seal defects, delamination, product leakage through holes, tears or nonbonded seals, malformations, and crushed or deformed areas. This inspection should be followed by inspection of the production line equipment to quickly find causes for any abnormal package appearance. The following information is excerpted from NFPA Bulletin 41-L, "Flexible Package Integrity Bulletin."

28.10.3 TEARDOWN PROCEDURES FOR PAPERBOARD PACKAGES

Unfold all flaps (except gable top packages) and check the integrity and tightness of transverse (top and bottom) and side (vertical or longitudinal) seals by squeezing the package firmly. Evidence of leakage or other critical defect(s) requires immediate remedial action.

If the package has a longitudinal sealing (LS) strip, pull off the overlapping paper layer at the side (longitudinal seal). Check the air gap of the longitudinal sealing strip application (~1 mm). Squeeze the package and check that there are no leaks or holes in the LS strip.

Next, on the side opposite the side seal, puncture the container with sharp scissors and empty the contents. Saving the side seal side, cut near the fold at each end of the package and down the length of the package to remove a large rectangular body portion and inspect for holes, scratches, or tears anywhere on the surface. Pay close attention to the corners of the package, particularly directly under the end seals and near the straw hole or pull tab, if present.

Now cut the remaining package in half by cutting across the center of the side seam. Wash both halves of the remaining package and dry them with a paper towel. Mark to identify the package.

Evaluation methods for seal quality differ between package designs, constructions, and sealing methods. Specific procedures for a given package should be obtained from the manufacturer. For example, seal evaluation may consist of starting at one end of the seal and very slowly and carefully pulling the seal apart. In some manufacturers' packages, the seal is good if polymer stretch (continuous presence of stretching polymer film at a point beyond where the paper and laminates have separated) is seen throughout the entire length of the seal. In other manufacturers' packages, fiber tear (raw paperboard is visible on both sides of the separate seal areas) will be seen the entire length of the seal in good packages. Test all three seals of each package half. Problems to look for are absence of or narrow fiber tear, lack of polymer stretch, "cold spots" (no polymer bond in seal area) and "tacking" (polymer melt but no stretch or fiber tear).

For longitudinal sealing of strip-type packages, additional tests such as centering examination, heart mark examination, and appearance of aluminum foil when stripped, should be made according to the manufacturer's directions.

28.10.4 TEARDOWN PROCEDURES FOR FLEXIBLE POUCHES

Check the tightness of both head and side seals by squeezing each of the packages from each fill tube or sealing lane. Important points are corners and the crossing point of the head and side seals. (This is a rapid determination of obvious defects. All seals must be accurately torn apart and evaluated for correct integrity of each seal.)

Carefully inspect the edges of each seal for any evidence of product in the seal areas. No product should be visible. Observe the width of each seal area. The width must comply with machine-type specifications.

Open each package to check side seals and head seals. Visually inspect for such defects as: misaligned seal, flex cracking, nonbonding, and seal creep.

If applicable, tear the seals by doing a seal tensile strength test, or a burse test. Then observe the appearance of the tear at each seal. The seals should be torn evenly in such a way that the foil, and part of the laminated layer from one side of the package, tears off adhering onto the seal on the other side of the package. The seal should now appear rough and marbled. The seal may also be considered adequate if the foil is laid bare across the entire length of the seal or as above.

Retain records of test results as required.

28.10.5 PEEL TEST PROCEDURES OF FORM, FILL, AND SEAL CONTAINERS

Squeeze the container sidewalls of the entire set from a mold. Each cup should be squeezed to cause a 1/8" bulge of the lid area. (The lid should not separate from the package when the package is squeezed. Observe the sealing area for fold-over wrinkles in the sealant layer of the lidstock.) Also, observe the embossed ring in the seal area for completeness. (This embossed ring should be at least 90% complete in total, if present.)

Remove a second set of containers (one cup per mold) and gently peel back each lid at approximately a 45° angle. Observe the "peeled" area for a generally frosty appearance on both the lid and cup sealed surfaces. (This is a good quality in most packages.)

Observe the entire package for holes, scratches, uniform flange widths, smooth inside surfaces, and any deformities caused by a dirty mold or sealing die.

28.11 TEST METHODS FOR PACKAGE INTEGRITY

The various test methods are summarized in Table 28.2. Each test has advantages and disadvantages depending upon the package, equipment and set of conditions. Optional methods are appropriate

TABLE 28.2

Test Methods for Aseptically Filled and Sealed Packages Containing Food

Test Method		Package Type			
		PP	FP	HSC	MC
1	Air leak testing	O	O	O	O
2	Biotesting	O	O	O	O
3	Burst testing	O	X	X	NA
4	Chemical etching	O	O	O	NA
5	Compression, squeeze testing	X	X	O	NA
6	Distribution (abuse) test	O	O	O	O
7	Dye penetration	X	OX	O	O
8	Electester	O	NA	NA	O
9	Electrolytic test	X	O	X	NA
10	Gas leak detection	O	O	O	O
11	Incubation	X	X	X	X
12	Light	NA	O	O	O
13	Machine vision	O	O	O	O
14	Proximity tester	O	O	O	O
15	Can seam teardown	NA	NA	NA	X
16	Sound	X	NA	X	O
17	Tensile (peel) testing	NA	O	X	NA
18	Vacuum testing	NA	O	X	O
19	Visual inspection	X	X	X	X

Note: X = Recommended test method; O = Optional test method; NA = Not appropriate for this style package; PP = Paperboard packages; FP = Flexible packages; HSC = Plastic packages with heat seal lids; MC = Metal can with double seam.

when additional information will clarify the nature of various package defects. Some test methods are not appropriate for some package materials, closures, or package styles. Refer to the manufacturer of the package or closure system for recommended test methods. All common methods are presented to provide the analyst with all of the procedures and options.

Make all measurements of packages before any micro-leak testing. Visually detected defects should be marked to aid location during or following micro-leak testing. Markers having inks that are not water soluble are recommended for this purpose. Record all results, methods used, and environmental conditions (temperature, relative humidity) and retain these records.

All testing should be conducted in the standard laboratory atmosphere of $23 \pm -2^\circ\text{C}$ and $50 \pm -5\%$ relative humidity. When this is not possible, the temperature and relative humidity should be reported along with test results.

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29 Biovalidation of Ohmic Processing Systems

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29.1 INTRODUCTION

Ensuring commercial sterility of continuously processed foods containing particulates cannot be based on conventional in-container thermal process calculations because time/temperature measurement in particulates is not possible as they move within the aseptic and/or Ohmic processing systems. In absence of the physical means for temperature measurements, biological validation appears to be the only alternative available to evaluate the lethality (F_0) delivered at the center-point of the largest/fastest moving particle in an aseptic and/or Ohmic processing line. According to Ronner (1990), the principle of biological validation is to evaluate the thermal process, which has a chosen F_0 value, by using a selected indicator organism that is recovered and quantified. Biological validation can be performed by direct inoculation of free bacterial spores into the product prior to the process or into particulates carried through the process. Direct inoculation is of minor interest because of (a) its low sensitivity as only a small proportion of the total inoculation level of bacteria is recovered after the process, and (b) temperature measurements for homogeneous liquid products processed in aseptic and/or Ohmic lines (Ronner, 1990; Pflug et al., 1990). Inoculation of food particulates is a simple concept, but for some reason it received more attention from researchers. This is attributed to the dynamics and characteristics of particle movement in an actual Ohmic aseptic processing system, which is as complex as the heat penetration into the particles (Dignan et al.,

1989). It is worthwhile noting that the use of biological indicators will only give an integrated sterilization value for the entire process under consideration (heating, holding, and cooling). It is next to impossible to isolate the thermal and lethal effects of the individual sections of any continuous aseptic and/or Ohmic process.

The prevalent belief based on models, experimentation and the laws of physics, is that particles in an Ohmic process can heat faster than the surrounding fluid if the product considered is correctly formulated (Kim et al., 1996). The only issue with this statement is in producing quantitative proof which to date has been, at best, theoretical. The main reason for the culmination of theoretical data lies in the fact that it is extremely difficult to measure the temperatures of particles in a continuous flow Ohmic system. Moreover, temperature measurement is complicated by the presence of an electrical field (Sastry and Salengke, 1998). Currently there is no physical method available for measuring temperature within a real particle of food undergoing continuous Ohmic processing (Kim et al., 1996). Several techniques were investigated to capture the temperature profile of particles such as liquid crystals and magnetic resonance imaging (MRI), stationary fluid assumptions, stationary particle methods, moving thermocouple method, remote temperature sensor, relative velocity measurement/particle tracking velocimetry, melting point indicator, liquid calorimetry, solid calorimetry, microbiological methods, and thermal history methods (Sastry and Cornelius, 2002). Detailed discussion of the heat-transfer methods is beyond the scope of this chapter. It is worthwhile noting that most of these methods were developed for conventional aseptic processing, but some of them may be extended to Ohmic heating with modifications that take into account the nature of the electric heating and how food systems can react to it. For example, liquid crystals can only be used for transparent food systems, while MRI measurements are limited by the need to turn the electrical field off for 14 s during data acquisition. Other approaches that have been implemented with success are biological (microbial or enzymatic), or chemical in nature (Sastry and Salengke, 1998). There is ongoing research into the ways and means of measuring particle temperature in an Ohmic processing system.

Since temperature is the principle critical factor for the design of an adequate Ohmic process, data availability for the validation of the process lethality, especially for shelf-stable low-acid foods containing particulates, is a critical requirement. The key to Ohmic heating process validation is the ability to locate the zone of minimal thermal treatment commonly referred to as the cold spot in the product (Sastry, 1992; Sastry and Cornelius, 2002). United States regulations on low-acid canned foods (Title 21 parts 108 and 113 of the United States Code of Federal Regulations) require a demonstration of a product's safety along with a process established by a qualified Process Authority (Larkin and Spinack, 1996). In conventional canning, the cold spot is usually the geometric center of the container when undergoing a static retort process. However, in Ohmic heating, establishing the cold spot in the product is more complex and difficult because of all of the inter-related parameters (carrier fluid density and viscosity, thermal conductivity, thermal diffusivity, electrical conductivity, percentage particle loading, particle size, particle density, etc.) that affect the heating rate of different particles in two-phase low-acid food systems as discussed in previous chapters. For single-phase homogenous fluid foods, the cold spot is typically the fastest moving region of liquid. But in solid-liquid mixes, the cold spot will depend on the electrical conductivities of each phase in addition to the many other inter-related complex factors as outlined above (Sastry, 1994; Sastry and Salengke, 1998; Larkin and Spinack, 1996). The situation is further complicated by the fact that temperatures within the solid phase cannot be measured directly during the Ohmic process due to the continuous nature of flow. Therefore, mathematical models and microbiological methods have been used extensively for validation of aseptic and Ohmic processes—a method referred to as biovalidation (Kim et al., 1996). The main universally accepted biological methods utilize either the death or survival of microorganisms or chemical changes in the product. Therefore, most of the discussion in this chapter will be concentrated on microbiological validation.

The utilization of survival and death of inoculated microorganisms is by far the most accepted biovalidation practice for aseptic processing of low-acid foods. The Campden Food and Drink

Research Association in England was the first to develop a method for assessing the lethality delivered to particles in an aseptic process (Gaze et al., 1989; Parrott, 1992). They employed the use of sodium alginate beads blended with a food material inoculated with the spores from a test organism. The choice of the test organism depends on its heat resistance and the target process temperature (Gaze et al., 1989). The surrogate microorganisms used as biological indicators should closely mimic the organism targeted for destruction by the process. Surrogates should be well-known, nonpathogenic organisms that have similar growth habits and heat resistance in comparison to the target organism. The microorganisms should not be susceptible to injury, irreversible inhibition or genetic instability (Grischy et al., 1983).

For low-acid foods processed to commercial sterility, *Clostridium sporogenes* is the microorganism of choice for use as a surrogate for *Cl. botulinum*, a highly pathogenic organism that produces one of the most potent neurotoxins known to man (Gaze et al., 1989; Kim et al., 1996). For low-acid products intended to be processed to attain commercial sterility, the process must be designed to deliver a “*botulinum cook*” or a heat process that reduces the population of the most resistant *Cl. botulinum* spores by a factor of 12 decimal values (12-*D* Process). This process promotes a substantial margin of safety, allowing for only one spore to survive out every one billion (10^{12}) thermally processed containers. Spores of *Cl. sporogenes* are more heat resistant than the spores of *Cl. botulinum*, but they are nonpathogenic. According to Grischy et al. (1983), the strain most commonly used to biovalidate low-acid food processes is Putrefactive Anaerobe (PA 3679), a strain isolated by the National Food Processors Association (currently known as Grocery Manufacturers Association, GMA).

Most biovalidation studies of low-acid retorted food products occur through direct inoculation of the product at the geometric center of each individual container with a known amount of *Cl. sporogenes* spores. However, in continuous processes with particulates, the coldest spot is much harder to determine. For most aseptic and/or Ohmic processes of liquid and solid mixes, inoculation of the particles is the best approach to test the potential cold spot in the product because heating is still governed by conduction. In Ohmic heating processes, there is evidence to suggest that the particles can heat faster than the carrier liquid, but there is no established easy way to measure temperature within the particles during the Ohmic process. Consequently, inoculation of the particles is probably an acceptable technique to examine this hypothesis. However, in an Ohmic processing system if it can be demonstrated that the temperature of the presumed cold spot of the slowest heating particle was the same or higher than that of the liquid when it entered the hold tube, a biological challenge of the system would not be necessary as a component in establishing the Ohmic process. The Process Authority could solely rely on the time and temperature of the liquid in the hold tube (Larkin and Spinack, 1996). Since, this is yet to be shown; Ohmic processors continue to validate their processes based on inoculated particles studies.

The first inoculated particles were developed by Dallyn and a coworker in the 1970 s as a means of biovalidating a UHT system (Dallyn et al., 1977; Bean et al., 1979). Sodium alginate was used to immobilize spores of the target organism by adding the bacterial spore suspension to a sterile sodium alginate solution and mixing thoroughly for even distribution. The alginate/spore mixture was then transferred to a sterile syringe. Using the syringe, the mixture was dispensed through a needle and dropped into a sterile calcium chloride solution. Upon contacting the calcium chloride solution the alginate/spore mixture immediately gelled and beads were formed. The syringe enabled the production of a more uniform and consistent volume of beads. Over time, the calcium replaced the sodium in the alginate mix (Dallyn et al., 1977; Gaze et al., 1989). These beads can be used alone, mixed with a food matrix, or can be embedded in a food matrix. Any shape can be manufactured in any size. According to Gaze et al. (1989), adding the food matrix can enhance the environment for the organism, ensuring moisture and a food source upon germination and growth. Gaze et al. (1988) used an alginate/food/spore matrix to study the lethality of a dynamic flow sterilization system. They used spores of *Cl. butyricum* mixed with a peach puree and alginate solution formed into either beads or cubes (Gaze et al., 1988). Earlier, Brown et al. (1984) investigated the

destruction of *Cl. sporogenes* spores immobilized in a potato/alginate matrix. They tested immobilized spores to determine the feasibility of using inoculated food/alginate particles mixed with actual food particles to estimate the lethality of a thermal process.

When the alginate/spore beads have been thermally processed, they are retrieved from the food or food matrix (if inside of a cube or sphere) and tested for viability. For immediate results and quantification, the beads can be suspended in either potassium or sodium citrate and vigorously shaken. These chemicals help to break down the alginate and release the spores into the solution (Dallyn et al., 1977). For qualitative testing, the beads can be transferred to a growth medium and incubated for a prescribed period of time until growth can occur. In either case, it is imperative to have the proper growth medium for heat-damaged organisms or spores. In the case of outgrowth of *Cl. sporogenes* (PA 3679) from thermally processed low-acid foods, there are just a few media of choice.

Once the inoculated product has been subjected to varying levels of heat at constant time intervals, the product is incubated at an optimum germination temperature for the test organism. For low-acid products inoculated with *Cl. sporogenes*, the temperature would be 95°F (35°C) for a minimum of 28 days. Any container that swells during the incubation period is analyzed to ensure that the cause of the spoilage was the test organism. PA 3679 media is often used to subculture the product from the swollen containers. In addition, subculturing procedures as outlined in the *Compendium of Methods for the Microbiological Examination of Food and the FDA Bacteriological Analytical Manual* can be used to assess the type of spoilage encountered (Denny and Parkinson, 2001; and Landry et al., 1998). In some cases, a microbial characterization method that produces DNA patterns of the organism (such as DuPont Riboprinter®) can be used to compare spoilage organisms to the test organism, verifying source of spoilage. Also, at the end of the required product incubation, any temperature levels that do not show signs of spoilage are subject to subculturing analysis using PA 3679 media. Usually the two higher temperature-processing levels above the last one showing spoilage are subcultured. Based on the results of the biovalidation, the thermal process is either validated that it delivered the intended lethality or not.

29.2 BIOLOGICAL VALIDATION FOR PARTICULATE FOODS

29.2.1 BIOLOGICAL INDICATORS

One of the methods for biologically evaluating the lethal (bacterial-killing) power at the particle geometric center (assumed to be the slowest heating location) is known as the “biological thermocouple system,” which has been used in Europe and North America for almost 50 years. It is called the biological thermocouple system because the spores in the biological indicator unit are not in contact with the food product. The spores are placed in a carrier such as glass that is located in the center of the food particle. According to Cousin (1993) and Hersom and Shore (1981), the method has several advantages: (1) the location of the spores is known; (2) all the spores in a bulb are recovered once the bulb is recovered; and (3) all the spores can be located at the geometric center. Pflug and coworkers (Pflug and Smith, 1977; Pflug et al., 1980; Pflug, 1982; Pflug and Zechman, 1983) have used the biological thermocouple with a great deal of success.

29.2.2 INOCULATED PARTICLES

An alternative approach which has been used for many years is the inoculation of the slowest heating location of real food particles with heat-resistant microbial spores (e.g., *Bacillus stearothermophilus* and *Cl. sporogenes* (PA 3679)) and evaluate their survival on exit of the Ohmic processing line. The presence of calibration data for the purpose of comparison is not only essential, but critical. Dignan et al. (1989) and Pflug et al. (1990) listed a number of obstacles to be considered when a thermal process for particulates is biologically validated: (1) the conditions affecting spore destruction must

mimic the actual processing situation; (2) an effective N_0 must be determined in case of a leakage possibility; (3) N_0 must be adjusted in all calibrations; (4) particles must maintain their integrity and size during testing; (5) residence time of the inoculated particles must be representative of the fastest particle; (6) the location and distribution of the spores in the particles must be known; and (7) the z -value of the spores must be determined in order to properly use the time–temperature data.

Sastry et al. (1988) used an infusion procedure where mushrooms were placed in a spore suspension for 36 min. The choice of mushrooms was based on the following reasons: (1) availability in large sizes, permitting conservative testing; (2) high porosity of fresh product, facilitating infusion of bacterial spores; (3) a well-characterized albeit-irregular geometry; and (4) easy local availability. However, these indicators were not tested in a commercial aseptic system for mechanical sturdiness and durability.

Sastry (1989) summarized the desirable/necessary characteristics for a bioindicator as follows: (1) large size (2.5 cm); (2) presence of heat-resistant spores throughout the interior, especially the slowest heating point; (3) geometry and thermal properties must be similar to real food particles; (4) visual distinguish-ability from real food particles, to facilitate recovery from the processed product; (5) retention of spores without leakage throughout the process; (6) shelf stability permitting easy reconstitution and use whenever desired; and (7) physical durability to withstand process stresses without disintegration.

Cerney et al. (1989, 1990) utilized formulated food particles of egg white ovalbumin and potato alginate cubes to determine the lethality of immobilized *B. subtilis*, *B. stearothermophilus*, and *Cl. sporogenes* after heat treatment. The spores in particles are less rapidly inactivated than those heated in phosphate buffer for the same time–temperature combination. The D -values determined were 1.5- to 2-fold higher in particles than in the phosphate buffer. Increased thermo-resistance was observed with fat containing particles, but this may be reduced by the addition of emulsifiers. Denatured proteins (ovalbumin) and some starches were reported to have the same effect. Low water activity persistent in particles may be implicated, but the real reasons behind this phenomenon are yet undetermined. Ovalbumin particles containing *Cl. sporogenes* were used to study the distribution of thermal energy by incubating the heated particles at 37°C for 48 h, and then particles were sliced to visualize the black spots where spore survival is indicated by sulfite reduction (Cerney et al., 1989). Similar experiments were performed with potato cubes and peroxidase enzymes activity.

29.2.3 SIMULATED PARTICLES

The problems associated with the biological validation of continuous aseptic processes when actual food particulates are inoculated with bacterial spores have led researchers to develop simulated particulates. Hunter (1972) used polymethylmethacrylate to suspend bacterial spores but, in this plastic material the spores are subject to dry heat destruction. The use of alginate gel particles inoculated with spores to validate thermal processes was reported by Dallyn et al. (1977). The alginate particles were made by mixing bacterial spore with a sterile sodium alginate solution, and then drops of the mixture were introduced into a sterile calcium chloride solution to induce gelation. The resulting beads were reported to have an excellent mechanical strength to withstand processing conditions in a scraped surface heat exchangers. This approach has been employed by Bean et al. (1979) to determine the lethalties achieved in a commercial aseptic system using *B. stearothermophilus* and by Heppell (1985) to determine the fluid-to-particle heat-transfer coefficient. However, the particle sizes used in all of these studies were very small (1.6–3.2 mm).

Brown et al. (1984) immobilized *Cl. sporogenes* in large (0.8–2.4 cm) food alginate particles made from pureed potatoes, peas, and meat. The test microorganism had D -values of 0.7 and 0.8 min in potato-alginate and meat-alginate particles, respectively. The z -values for the temperature range of 115–130°C were 12.5°C and 12.7°C, respectively. Experiments with alginate-food particles showed encouraging success for further research. Moreover, the alginate-food particles have a long shelf life and are harmless to the immobilized bacterial spores.

A further development was introduced by Ronner (1989, 1990) who constructed a commercially available bioindicator from polyacrylamide gel (PAG) containing *B. stearothermophilus*, as the alginate-food particles are susceptible to disintegration in contact with chemical environments containing calcium chelators and can shrink during processing causing changes in shape and thermal diffusivity. The PAG particles are colorless, stable and tough, maintain shape, do not leak unless mechanically damaged, and have an impermeable outer layer, but an internal microporous structure to allow fast heat diffusion. The main disadvantage is the size of these particles (8 mm) may not be a true representative for the validation of aseptic processing of larger particles.

29.2.4 CHEMICAL INDEX MARKERS

It is well documented that biological indicators offer the most direct proof of sterility, but it is rather tedious and its use under varying process parameters (temperature, flow rate holding tube length, particle size, system configuration, etc.) has limited value (Kim and Taub, 1993). Monitoring chemical changes within the food, which involves compounds either indigenous to or added to the food, offers an alternative route for assessing the integrated time–temperature exposure of the food particulate. These are the chemical indicators that have been used for process validation. Such examples include the loss of thiamin (Mulley et al., 1975), peroxidase (Adams et al., 1984; Weng et al., 1992), pantothenic acid (Hamm and Lund, 1978), ascorbic acid (Rao, 1992), anthocyanin (Tanchev, 1983), and methylmethionine sulfonium, MMS (Berry et al., 1989). The major disadvantage with these markers is that their loss is quite small for the same process lethality at high temperatures/short-time treatments associated with conventional aseptic processing and/or Ohmic heating, because the z -values for typical chemical reactions are much higher than those for thermal destruction of microbial spores (Lund, 1977; Jelen, 1983). A good example of this is the thiamin destruction in beef puree for which the D -value is 244 min and the z -value is 48°F (Mulley et al., 1975) in comparison with a z -value of 18°F for *Cl. botulinum*.

Researchers from the United States Army Natick Research Center (Natick, MA) used intrinsic chemical markers to validate aseptic and Ohmic processes (Kim and Taub, 1993). Using the analytical capabilities of anion exclusion chromatographic (AEC) separation and photodiode array (PDA) detection, Kim and Taub (1993) were able to identify some compounds formed in foods as a result of thermal processing (aseptic processing and/or Ohmic heating). Three intrinsic chemical compounds were detected by a three-dimensional representation of AEC-PDA. M-1 (2,3-dihydro-3,5-dihydroxy-6-methyl-(4H)-pyran-4-one) was detected in heated chicken meat, vegetables (potato, green bean, pea, carrot), and fruits (apple, orange, pear) under varying time–temperature conditions. M-2 is associated with protein (aseptically processed meat and potato), but no chemical characterization was given as yet. M-3 is 5-hydroxymethylfurfural (HMF), which is well known as a major degradation product of D-fructose (Shaw et al., 1967). M-3 was detected from aseptically processed juice drinks and heated fruits and vegetables. The destructive kinetics of these intrinsic markers as defined above (M-1, M-2, and M-3) were studied and correlated to the time–temperature of the thermal process. The concept of thermal process validators is sound, practical and represents a step in the right direction, but more work is required to standardization. Researchers from the US Army Natick Research Center (Natick, MA) developed several intrinsic chemical markers that have been used extensively for studying uniformity of heating in various thermal processes including conventional aseptic processing, microwave, and Ohmic heating. They include 2,3-dihydro-3,5-dihydroxy-6-methyl-(4H)-pyran-4-one (or more commonly referred to a M1), 4-hydroxy-5-methy-3(2H)-furanone (M2) and 5-hydroxymethylfurfural (M3) (Lau et al., 2003). Both M1 and M2 (Pandit et al., 2006, 2007) are formed through a reaction between a sugar group and a protein during the heating processes (Lau et al., 2003). These thermally produced compounds are considered to behave as time–temperature integrators over a high-temperature short time period. Kim et al. (1996) used M1 and M2 in several lethality studies of Ohmic heating and conventional aseptic processes of low-acid two-phase foods. Furthermore, Lau et al. (2003) used both M1 and M2 to

demonstrate that higher lethality was achieved in the center of meatballs as compared to near the surface that were Ohmically processed.

More recently, a workshop was conducted in Chicago, Illinois (1995–1996) between academia, government, and industry to develop guidelines for the validation of aseptic processing of liquid foods containing particulates. The guidelines were developed for conventional aseptic, but they can be extended to other novel continuous thermal processing methods such as Ohmic heating and microwave processing. Validation of conventional aseptic and Ohmic heating systems requires accurate information on: (1) design and capabilities of the processing system; (2) formula and preparation procedures of the product intended for processing including percentage (%) particle loading, particle size, and type of particle; (3) physical properties of the product, including liquid and particles (thermal conductivity, thermal diffusivity, density, specific heat capacity, rheological properties; and interfacial heat-transfer coefficient; (4) microbiological characterization of the organism used to validate the process: determination heat resistance (D and z -values) by thermal death time (TDT) study; and finally (5) a mathematical model to simulate the process and predict processing conditions.

29.3 VALIDATION OF OHMIC PROCESSES

It has been established that the mechanism of microbiological destruction in Ohmic heating of foods is thermally based (Sastry and Barach, 2000). Moreover, NACMCF (2006) concluded that Ohmic heating is a rapid, volumetric, and uniform thermal process and the most heat-resistant pathogen is likely to be the same as that of other thermal processes. To date no microorganisms or pathogens of unusual resistance to Ohmic heating have been identified. For process optimization purposes, it may be desirable to understand and establish if additional nonthermal mechanisms contribute to microbial inactivation. This may lead to utilization of Ohmic heating as a mild thermal process, such as in pasteurization. According to Sastry and Barach (2000) and Palaniappan et al. (1990) early literature is inconclusive, since temperature had not been completely eliminated as a variable. Recent literature has eliminated thermal differences, but has indicated a mild electroporation mechanism may occur during Ohmic heating. This may be attributed to the additional effect of the low frequency (50–60 Hz) associated with Ohmic processing, leading to cell walls charges build-up and pores formation. This is in contrast to high-frequency methods such as radio frequency or microwave heating, where the electric field is essentially reversed before sufficient charge buildup occurs at the cell walls. Therefore, the principles of validation of conventional aseptic processing of low-acid foods containing particulates can be applied to Ohmic heating. According to Palaniappan and Sastry (1992) and Lee and Yoon (1999), it is critical that studies comparing conventional aseptic processing and Ohmic heating are conducted under similar temperature conditions. They found no difference between the effects of Ohmic and conventional heat treatments on the death kinetics of yeast cells (*Zygosaccharomyces bailii*) and *Bacillus subtilis* spores, under identical processing regimes. The heat sensitivity values (z -value) for *Zygosaccharomyces bailii* were 7.19°C and 7.68°C for conventional heating and Ohmic heating; respectively (Palaniappan et al., 1992). Similarly the z -values for *B. subtilis* were 8.74°C and 9.16°C for conventional heating and Ohmic heating; respectively (Cho et al., 1999). This is an indication that the main mechanism of microbial destruction is thermal in nature.

There is only limited research indicating that in some cases, a mild electrical pretreatment of *B. subtilis* decreased their subsequent inactivation requirement (Table 29.1). This may indicate the existence of nonthermal effects of Ohmic heating. More research is needed to fully comprehend the inactivation mechanism of the various microorganisms, particularly the ones of public health significance. Currently, for almost all Ohmic processes that solely rely on heat, it is unnecessary for food processors to claim this effect in their process filings. Future processes may be reduced, if sufficient data are available to effectively substantiate the other mechanisms of Ohmic heating.

TABLE 29.1

D-Values and Reaction Rate Constants (k) for Inactivation of *Bacillus subtilis* Spores during Single- and Double-Stage Conventional and Ohmic Heating at 90°C

Stage Number	D-Value (min ⁻¹)		k (s ⁻¹)	
	Conventional Heating	Ohmic Heating	Conventional Heating	Ohmic Heating
1	17.1	14.2	0.002245	0.002703
2	9.2	8.5	0.004172	0.004516

Source: Cho, H.-Y., Sastry, S.K., and Yousef, A.E. Kinetics of inactivation of *Bacillus subtilis* spores by continuous or intermittent Ohmic and conventional heating. *Biotechnology Bioengineering* 1999. 62(3): 368–372. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

Data on the effect of Ohmic heating on enzymes and kinetic factors (color, texture, and other nutritional factors) is somewhat limited (Vincente et al., 2006). This may be attributed to the fact that no attention was given to the Ohmic heating technology in the past. Only recently researchers and the food industry started to show some interest in the technology. Some research was conducted on the inactivation kinetics of pectinase (PEC) and alkaline phosphatase (ALP). It was demonstrated that Ohmic heating has no significant influence on the inactivation kinetics of the enzyme compared to conventional heating methods. Vincente et al. (2006) demonstrated that the z -values for PEC (z -value was 8.11°C for Ohmic and 7.75°C for conventional heating) and ALP (z -value was 9.00°C for Ohmic and 9.34°C for conventional heating) were somewhat similar. The authors also reported identical trends for polyphenoloxidase (PPO) and β -galactosidase (β -GAL).

Consequently, the Ohmic process validation must address and consider all critical factors when establishing the efficacy and equivalency of different Ohmic processes. This includes the identification of the most resistant pathogen(s) of public health concern, the ability of the Ohmic process to reduce the pathogen(s) of concern in the food, the food matrix characteristics, and the intended use of the food. The following guidelines are normally used to validate new technologies (NACMCF, 2006): (1) identify the microorganism(s) of public health concern by conducting hazard analysis, (2) establish the most heat-resistant pathogen of public health concern that is likely to survive the Ohmic process, (3) determine the required level of inactivation. Initial microbial load and normal variations in concentration that are more likely to occur must be considered, (4) evaluate the effect of the food matrix on pathogen survival, (5) validate the efficiency of the Ohmic process, (6) identify and define the critical limits required during processing to meet the desired sterilization target, and (7) define the specific Ohmic processing equipment and the operating parameters for the proposed sterilization process.

29.4 VALIDATION/CRITICAL PROCESS FACTORS

29.4.1 IDENTIFICATION AND DESCRIPTION OF CRITICAL PROCESS FACTORS

It is established that Ohmic heating is fundamentally a thermally based process, based on microbial, enzymatic, and quality factor kinetics as discussed above. Consequently, time and temperature are the principal critical process factors for process establishment. Unlike conventional aseptic processing, Ohmic heating is an internal energy generation process. As a result, there is theoretically no upper temperature limit to the process (Sastry and Barach, 2000). Thus, if product hold-up occurs, it is possible for boiling to occur within a system with high pressures.

As in conventional aseptic processes, the key limitation is the establishment of the point(s) of minimum thermal treatment. Fundamentally, then, there exist only two major critical factors, time and temperature of treatment at the slowest heating point. Several other factors, however,

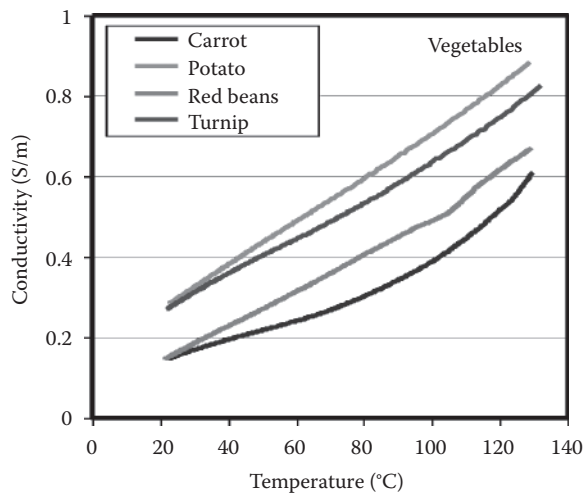


FIGURE 29.1 Electric conductivity of vegetables as influenced by temperature.

significantly affect the temperature within an Ohmic process. In a continuous flow Ohmic heating system, the electrical conductivities of the respective phases of the food (carrier fluid and solid particles) and the temperature dependence of electrical conductivity are the most critical factor affecting Ohmic heating (Vincente et al., 2006). Figures 29.1 through 29.3 illustrate the electric conductivity of various food materials (vegetables, meat, and ham) and its dependence on temperature. Electric conductivity has almost a perfect linear relationship with temperature. Products with added salts and preservatives like ham exhibit significantly higher electric conductivities (Figure 29.3) compared to untreated vegetables and meat products. Accurate data on electric conductivities of a product to undergo Ohmic heating is a must to design and validate a safe process. Mathematical models for Ohmic heating must address the electric conductivity and its dependence on temperature for accurate realistic design, its subsequent validation and filing with regulatory agencies.

For Ohmic processing of two-phase (solid–liquid mixtures) low-acid foods, the identification of the location of the slowest heating spot (least lethal treatment) is critical to process establishment

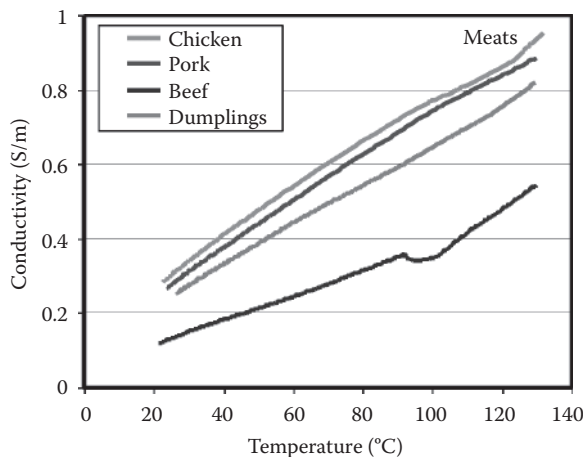


FIGURE 29.2 Electric conductivity of meats as influenced by temperature.

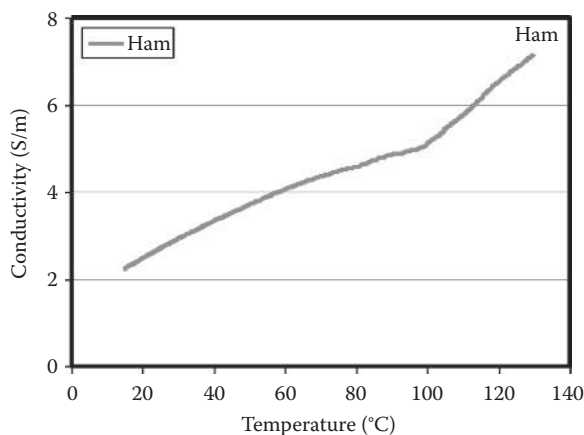


FIGURE 29.3 Electric conductivity of ham as influenced by temperature.

and validation. Early modeling work that was performed using a static Ohmic system showed the effects of differences in electrical conductivity between a single low- or high-conductivity particles (referred to as inclusion particles) located within a medium of significantly different electrical conductivity (de Alwis and Fryer, 1990a, b, 1992; de Alwis et al., 1989; Fryer et al., 1992; Fu and Hsieh, 1999). Further work by Sastry (1992) and Sastry and Palaniappan (1992) showed that the less conductive solid phase (food particles) in high concentrations could heat faster than the carrier fluid, but an inclusion particle may still provide a worst-case scenario. A concerted effort was devoted to the determination of the worst-case scenario within an Ohmic processing system (Zhang and Fryer, 1993; Sastry and Salengke, 1998), because it is critical to the validation process. Special attention must be given to particle (s) fat contents. According to Sastry (1992), if a fat globule is present within a highly electrical conductive food, the electric current will bypass the globule and it may heat slower by conduction. Consequently, pathogens potentially present within the fat phase may receive the least thermal treatment and survive the process. Heating of the fat globule may then depend on the rate at which energy is transferred from the surroundings. Based on the foregoing discussion, a high heat-transfer coefficient may not necessarily relate to the worst case, since fluid motion tends to moderate heating in such situations. If a fat-rich (low conductivity) phase is aligned to significantly intercept the current, it is possible for such a zone to heat faster than the surrounding fluid. Nevertheless, utmost care must be exercised in establishing the process.

Regardless of the scenario under consideration, the worst case must be established and accounted for. Particle electrical conductivity and its temperature dependence are critical control factors that define the worst-case scenario. Additionally, the cold zone may shift considerably during the course of processing, depending on the relative electrical conductivities of phases. The exact details are likely to be equipment-specific; thus, a separate analysis may need to be conducted for each new system, product formulation, preparation procedures and minimum initial temperature prior to start of processing.

There are other critical factors that must be addressed in Ohmic heating of low-acid foods such as the design of the Ohmic heating system and temperature control, the nature of the carrier fluid motion, particle residence time distribution, thermophysical properties of the food (density, specific heat capacity, thermal conductivity, thermal diffusivity, carrier fluid viscosity, percent particle loading), and electric field strength. To date there are only two commercial manufacturers for Ohmic systems, and as a result there are no established standards to guide the design and fabrication of Ohmic equipment and how they operate.

The rate of foods heating in an Ohmic processing line is directly proportional to the square of the electric field strength (E) and the electrical conductivity (σ) as reported by Sastry (1994). Since

the electrical conductivity of almost all foods (Figures 29.1 through 29.3) increases with temperature (Palaniappan and Sastry 1991a,b; Halden et al., 1990; Parrott, 1992), Ohmic heating becomes more effective with increased temperature. According to Sastry (1994), this phenomenon may raise the possibility of runaway heating resulting in uneven heating (similar to microwaves), and the possibility of arcing due to deposition of proteinaceous material on electrode surfaces. Another major factor affecting electrical conductivity is ionic content. It is therefore possible to formulate products with salt levels designed for effective Ohmic heating. Therefore, the electric conductivity of both particles and the carrier fluid must be closely monitored.

The validation of an Ohmic process for low-acid foods containing particulates can be achieved by adopting the guidelines established 1995–1996, provided that only thermal credit is to be considered. Food industry, government regulatory agencies (FDA and USDA), 10 universities, and the National Food Processors Association, NFPA (currently known as the Grocery Manufacturers of America, GMA) met in workshops (November 14–15, 1995, March 12–13, 1996, and April 15, 1996) to develop the validation guidelines for aseptic processing of multiphase foods. According to Dignan et al. (1989) the following parameters must be addressed to ensure all the steps of validation are successfully completed: (1) identification and selection of the appropriate sterilizing value based on product, ingredients, preparation procedures, and electrical–physical–chemical properties, (2) development of a conservative model that predicts the sterilizing value achieved at the slowest heating zone in a particle by the time the particle reaches the end of the holding tube, (3) quantitative microbiological validation of the lethality delivered; and (4) a list of the critical factors and procedures to be used to document their control. Consequently, meticulous attention to detail in the equipment design, product formulation, experimental design; and data collection is a necessity for the development of an Ohmic process for a two-phase food product. Residence time distribution of particles, heat-transfer characteristics, and biological validation must be adequately addressed. Sastry and Cornelius (2002) stated that the validation process protocol must include the following:

1. *Proper design and operation of the Ohmic processing equipment:* The following factors must be adequately controlled: the flow rate, Ohmic heater and hold tube temperatures, pressure drop in the hold tube, back pressure, aseptic surge tank (if available), and the aseptic condition of the filler.
2. *Proper formulation of the product:* The control of the overall viscosity of the product, particle size, control of particle size, particle concentration, ingredients, and rehydration time and temperature. For Ohmic heating electric conductivity balance between the particle(s) and carrier fluid is a key to process modeling and subsequent process validation.
3. *Physical properties determination:* electrical conductivity and physical–chemical properties of all particles and carrier fluid must be determined accurately. They include pH, density, specific heat capacity, thermal conductivity, thermal diffusivity, interfacial heat-transfer coefficient (h_{fp}) and overall heat-transfer coefficient.
4. *Residence time distribution:* Measurement of residence time distribution of particles in the Ohmic heater and hold tube, and cooler.
5. *Model calculation:* Process calculations must be performed to design the Ohmic biological validation by a well-thought tested mathematical model.
6. *Biological validation:* Biovalidations are conducted using *Cl. sporogenes*, PA 3679 (a surrogate for *Cl. botulinum*). The biovalidation process calculations must utilize the entire Ohmic processing system and actual product intended for human consumption. At least process five temperatures must be used.
7. *Establishment of the final process:* The mathematical model must be used to design the final commercial production. The model must only account for the lethality delivered within the holding tube of the Ohmic line.

8. *Verification of the model-established process:* Actual production runs must be conducted to ensure that the calculated process performance under actual commercial production conditions. This is a food industry standard practice known as incubation pack studies.

According to the NCFST-FDA workshops, the process filing and documentations must include detailed information on all aspects of Ohmic process establishment. Below is an account of the biological validation of an Ohmic process establishment for a low-acid food containing particulates.

29.4.2 THE OHMIC PROCESSING SYSTEM DESIGN

Ohmic equipment design is critical for the delivery of the lethal effect required ensuring the microbiological safety of Ohmically processed low-acid food products. The designs of the commercially available Ohmic systems include electrodes that are located at various positions along the length of the product flow path (in-line field), or those located perpendicular to the flow (cross-field). The design considerations in each of these cases are different. In the in-line field design, the device generally operates at high voltage and relatively low current, while in the cross-field design the field strength is constant throughout the system. These are basic designs, and a number of other possibilities exist, or are in development at this time. According to Sastry and Barach (2000), the issues associated with earlier design of Ohmic heaters are: (1) electrode corrosion, (2) system rigidity or inflexibility which is the tendency to adapt the product to the design characteristics of the Ohmic heater, rather the reverse; and (3) systems are relatively expensive investment. Recent innovations in Ohmic system designs allow for different configurations of heaters and considerable reduction of costs. This is achieved by the development of high-frequency switching power supplies at 25 kHz as opposed to earlier designs, which result in the elimination of metal release from electrodes into the product.

The ideal Ohmic system consists of a blending and product preparation platform to adequately prepare the product for the Ohmic line. It is critical that the product preparation capacity meets the throughput of the Ohmic heater. The Ohmic aseptic processing system normally consists of Ohmic heaters for heating the product mix. The number of heaters and their configurations must be addressed to ensure successful microbiological validation. The system must be equipped with a holding tube sloped upward at 20.8 mm per linear meter (0.25 in./linear foot). A piston positive displacement pump (e.g., Marlin pump) can be used for pumping the product without jeopardizing particle integrity. A rotary lobe pump can be used to maintain the necessary back pressure on the system to prevent flashing. Tubular heat exchangers are used to cool the products as in conventional aseptic systems. Any suitable aseptic packaging machine may be employed for aseptically packaging the biological validation samples. The specifications of the Ohmic line must be documented in the process filing intended for submission for regulatory agencies.

Other product properties that may effect temperature distribution include the density and specific heat of the food product. High densities and specific heats are conducive to slower heating. The thermal conductivity of the food may be of relevance if the material is heterogeneous, but is of relatively low importance for homogeneous materials.

As in other thermal processes, it is necessary to identify the location(s) of cold zones and their motion. The thermal process must be sufficient to inactivate target pathogens to the desired extent at the location(s) of least lethal treatment. For a homogeneous fluid medium, such a position would likely be at the fastest moving region.

29.4.3 OHMIC SYSTEM INSTRUMENTATION

Residence time distribution measurements in Ohmic systems are essential for the determination of the fastest moving particle in the system. Such measurements must be done to ensure proper process design for the biovalidation. There are different instruments and techniques that can be

used for detecting tracer particles flowing through the Ohmic system as described by Segner et al. (1989), Chandarana et al. (1994), Tucker (1992, 1993), Tucker and Withers (1993), and Sastry and Cornelius (2002). Most recently Tulsian et al. (2009) introduced the use of radio frequency identification (RFID) tags to measure residence time in Ohmic and aseptic systems. It is worthwhile noting Kumar et al. (2009) indicated that RFID tags may also be used for temperature monitoring.

One of the above methods can be used to detect food particles with embedded magnets or RFID tags in various sections of the Ohmic and/or aseptic processing system (at the inlet of each Ohmic heater, inlet and exit of the holding tube, and exit of each cooler). The temperature of the liquid carrier fluid of the product mix at the outlet of the product preparation mixers (product initial temperature)-inlet and outlet of each Ohmic heater, inlet and exit of the holding tube, and inlet and exit of each cooler—will be measured using thermocouples or RTDs installed in the product stream using the sanitary fittings. The collected data will be used to calculate processes for biovalidation of Ohmic processing of low-acid two-phase foods.

29.4.4 PRODUCT FORMULATION AND PREPARATION

All diced vegetables used in the product must be evaluated for particle size by measurements on all three dimensions. At least 299 particles from each particle type should be measured (Sastry, 1997). The minimum, maximum, mean, and standard deviations for all the measurements must be reported and considered in the process design for the biovalidation. The largest size particle is the one to use for process calculations. Particle size is a process critical factor that must be measured and controlled. A sample fictitious product formula is outlined in Table 29.2.

The product (mixed vegetable soup) consisted of a 14% mixture of potato cubes (1/2 inch), 6% carrot cubes (3/4 inch), 3% butternut squash cubes (3/4 inch), 3% modified corn starch and 2% bleached flour, and 6% soup mix (Table 29.2). The product was formulated by the full hydration of the modified corn starch, flour, and soup mix. The starch and soup mix were hydrated in water using the mixer and heated to a temperature of 150.0° (65.6°C) using ribbon blenders or tubular heat exchangers. It is critical for the preparation procedure to address issues of particles and dry ingredients clumping. After assurance of complete hydration of dry ingredients, the particles can be added to make the final product. The soup product can then be transferred to the system’s feeding tank. At that point, a sample can be drawn and tested for viscosity, specific heat capacity, thermal conductivity, thermal diffusivity, density, even particle distribution within the product, and particle loading. This is important to ensure the limits of the critical factors are within the established process boundaries. Some of the critical factors that are typically encountered in Ohmic processes are

TABLE 29.2
Formulation for the Mixed Vegetable Soup Product

Ingredients	Percentage (w/w)	Comments
Diced potatoes	14.0	1/2-inch cube
Diced carrots	6.0	3/4 inch cubes
Butternut squash	3.0	Irregular shapes
Modified corn starch	3.0	Pre-gelatinized starch
Bleached flour	2.0	To provide final viscosity
Soup mix		
Reduced fat milk powder	3.0	
Vegetable oil	1.5	
Dried potato flakes	1.0	
Seasonings and flavors	0.5	
Water	65.0	

TABLE 29.3
Batch Mixing Critical Limits/Factors

Factor	Maximum	Minimum
Carrier liquid viscosity	1000 cP at 150°F (65.6°C)	800 cP at 150°F (65.6°C)
Carrier fluid density	1.07 (g/mL)	
Maximum particles loading	28% (w/w)	
Soup mix preparation temperature		150°F
Mixed batching time		5 min
Hydration time at 150°F		20 min
Electrical conductivity of soup mix	$\sigma = 0.0045 T + 0.267$	
Electrical conductivity of diced potato	$\sigma = 0.0054 T + 0.188$	
Electrical conductivity of diced carrot	$\sigma = 0.0067 T + 0.262$	
Electrical conductivity of red beans	$\sigma = 0.0067 T + 0.170$	
Moisture of red beans after hydration		50% (w/w)

Note: σ is the electrical conductivity, T is the temperature.

listed in Table 29.3. The values in Table 29.3 are intended for guidance purpose and do not represent an actual product.

For safe process design for conventional aseptically and Ohmically processed products, it is critical that product formulation must have: (1) consistent uniform formulation composition with balanced electrical conductivity of all components, (2) free from clumping of constituents, (3) uniform mixing, (4) correct ratio of carrier fluid to particulates, (5) product interactions must be well understood to avoid situations that may lead to product breakdown or change of properties (density and/or viscosity) that may adversely influence process delivery, (6) shrinkage and swelling of product during processing that may result in changing thermal/physical/electrical properties; and (7) microbiological loading is critically important to process establishment and validation. The initial microbial load must be known and identified within each batch to insure process adequacy (Holdsworth, 1992). Successful, well-designed process validation must take into account all of these factors.

29.4.5 DETERMINING THE PHYSICAL PROPERTIES OF THE PRODUCT

Accurate determination of the physical properties is required to design the validation of the Ohmic process. These properties include specific heat capacity (C_p), thermal conductivity, thermal diffusivity, density, rheological properties, electrical conductivity, and heat-transfer coefficients. All of these properties are used as inputs in a mathematical model to design processes for the validation of the Ohmic heating process (Table 29.4). The model must take into account the most conservative physical properties values to insure a generous safety margin in process design.

29.4.6 BIOLOGICAL TEST SAMPLES

Food–alginate cubes containing a minimum of 1×10^5 uniformly distributed spores of the test organism (*Cl. sporogenes* (PA 3679)) are added to the vegetable soup intended for the biological validation tests of the Ohmic system. The food material in the food–alginate matrix must be consistent with the product to be validated. It can be a vegetable, meat based, or a mix there-of. A sufficient number of food–alginate cubes were processed in each test, to ensure the collection of the minimum required 299 intact particles as mandated by the CAPPS/NCFST workshop (Marcy, 1997; Damiano, 1997). The food–alginate cubes were prepared by a slight modification of the formula

TABLE 29.4**Summary of the Physical Properties for the Particles in Mixed Vegetable Ready-to-Serve Soup**

RTS Vegetable Soup	Density (kg/m ³)	Specific Heat Capacity	Thermal Conductivity (W/mK)	Thermal Diffusivity (m ² /s)	Reference
Diced potatoes (boiled)	1050	3.640	0.563	1.48×10^{-7}	Rahman (1995)
Diced carrots (boiled)	1040	3.766	0.571	1.55×10^{-7}	Rahman (1995)
Butternut squash (blanched)	1035	3.650	0.552	1.35×10^{-7}	Rahman (1995)

Source: Data from Rahman, S. 1995. *Food Properties Handbook*. CRC Press, Taylor & Francis Group, Boca Raton, FL.

TABLE 29.5**The Food–Alginate Formulation Used in Inoculation Tests**

Ingredient	Percentage
Food matrix	87.35
Distilled water	7.63
Alginic acid (sodium salt)	4.37
Calcium sulfate	0.36
Trisodium citrate	0.07
Yeast extract	0.10
Glucose	0.10
FeSO ₄ · 7H ₂ O	0.02
Total	100.00

used by Brown et al. (1984) as presented in Table 29.5. Each finished cube must contain at least 10^5 spores. The density of the food–alginate particles must be matched to that of the actual particles in the product.

The food–alginate cubes have been used as carriers for the spores in the biovalidation of thermal processes. This is attributed to the ease with which the inoculated cubes could be made and because the vegetable–alginate cubes were used as the carrier for the spores because of the ease with which the inoculated cubes could be made (Sastry and Cornelius, 2002). Planiappan and Sizer (1997) used potato–alginate for the validation of the low-acid condensed potato soup containing 1/2 inch potato cubes. Similarly other food matrices–alginate can be used for the validation of other food systems.

The thermal inactivation kinetics of the PA-3679 spores must be measured in the food–alginate formulation and the culture media through thermal death time (TDT) studies. The organism must exhibit kinetic characteristics that ensure adequate validation of the Ohmic process (D -value ($D_{250}^{\circ}\text{F}$) of 0.8–1.2 min and z -value of 15–20°F).

29.4.7 PROCESS CALCULATIONS

The design of the Ohmic process can be established, once all product characteristics, Ohmic system measurements and design specifications and microbial inactivation data are collected and verified. Usually mathematical models are used for this purpose (Sastry, 1994, 1997). The model is normally

based on the bulk fluid temperature (which can be measured from the Ohmic system). The following energy balance equation can be used:

$$\dot{v}_f \rho_f C_{pf} (T_f^{n+1} - T_f^n) = \sigma_f E^2 \Delta V_f + n_p h_{fp} A_p (T_{sm} - T_f^n) + U \Delta A (T_a - T_f^n) \quad (29.1)$$

where \dot{v} is the volumetric flow rate, ρ is the density, v is the volume, C_p is the specific heat capacity, T is the temperature, σ is the electrical conductivity, E is the electrical field strength, ΔV is the fluid volume at a given time interval with a flow rate of v_f , h is the heat-transfer coefficient between liquid and particle surface, A_p is the surface area of a single particle, ΔA is the pipe surface area at the given time interval with a flow rate of v_f , and U is the overall heat-transfer coefficient; Subscripts f , p , a , and sm represent carrier fluid, particle, air, and surface mean, respectively; superscript n is the locations or time step. The average particle surface temperature, T_{sm} is calculated by solving the governing partial differential equations:

$$\rho_p C_{pp} \frac{\partial T}{\partial t} = \nabla \cdot (k_p \nabla T_p) \quad (29.2)$$

where ρ is the density of the particle, C_p is the specific heat capacity, k is the thermal conductivity of particles, and subscript p represents the particles.

With a time-dependent boundary conditions:

$$k_p \nabla T_p \cdot \vec{n} = h_{fp} (T_s - T_f) \quad (29.3)$$

where T_s is the particle surface temperature and T_f is the liquid temperature.

Once the fluid temperature profile of the processing system has been developed, the core temperature of the worst-case particle can be simulated. The worst case is assumed that the particles move at a double speed compared with the average fluid speed.

The general integration method was used for the accumulated lethality value (F_o) at the particle center and integrated lethality value (F_v) for the whole particle as below:

$$F_o = \int_0^t 10^{T - T_r / z} dt \quad (29.4)$$

$$F_v = \int_0^t 10^{T_v - T_r / z} dt \quad (29.5)$$

where D is the decimal deduction time of the target microorganism (min), z is the decimal deduction temperature of D value for the target microorganism or quality factor ($^{\circ}\text{F}$), T_r is the reference temperature ($^{\circ}\text{F}$), and T and T_v represent the particle core temperature and volume temperature ($^{\circ}\text{F}$); respectively. Figure 29.4 shows the agreement between the Ohmic processing computer model predicted temperature of the carrier fluid compared to the data collected from the temperature probes installed on a typical Ohmic line. It is the responsibility of the food processor to provide the regulatory agencies with a detailed account of the computer model used for the process design.

Temperature profiles (135.0 $^{\circ}\text{C}$, 130.0 $^{\circ}\text{C}$, and 120.0 $^{\circ}\text{C}$) obtained from a typical Ohmic processing system in comparison to a computer model predictions (including particle center temperature) are given in Figure 29.5 for mixed vegetable soup. The model predictions were comparable to the actual system temperatures.

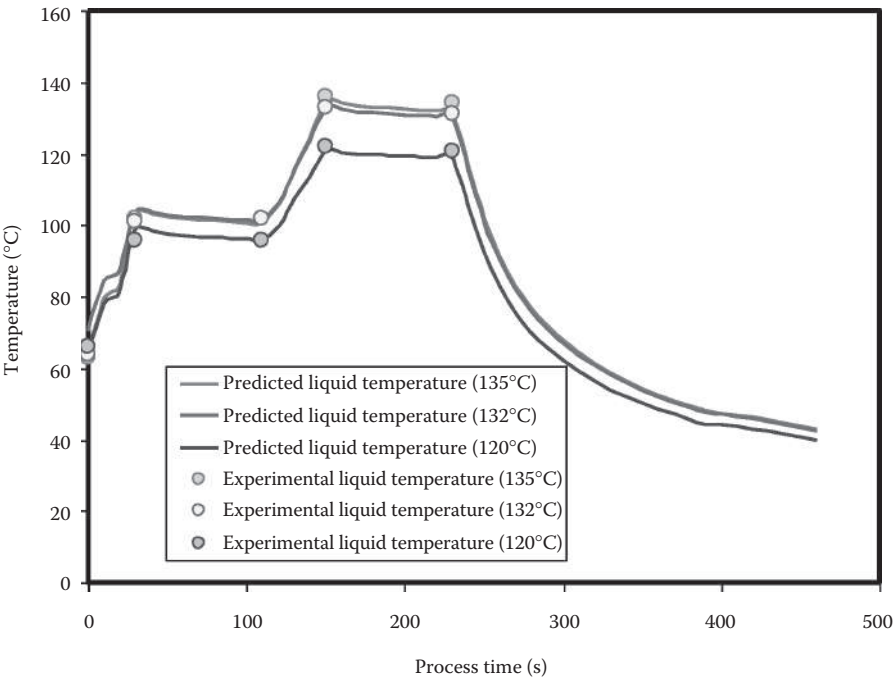


FIGURE 29.4 Ohmic computer model prediction of temperatures as compared to actual Ohmic processing line temperatures.

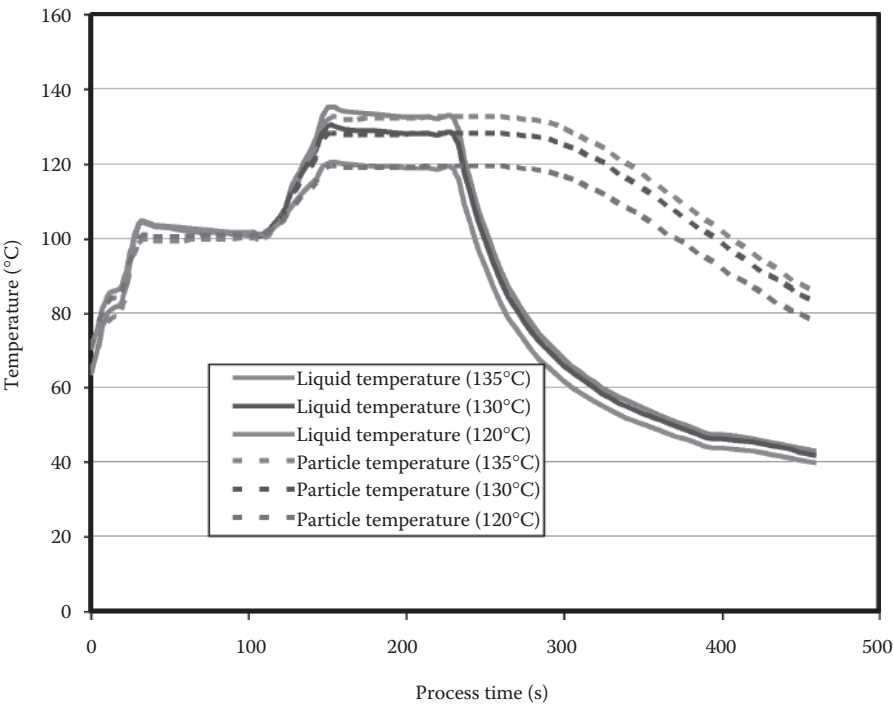


FIGURE 29.5 Graphical representation of a computer model predicted and actual time–temperature profiles (measured from Ohmic production line) for mixed soup used for biovalidation.

TABLE 29.6
Computer Model Based Lethality Calculations for Ohmic Process Validation

Carrier Liquid Temperature in the Holding Tube		Particle Temperature at the Holding Tube		Carrier Fluid Lethality (min)		Particle Lethality (min)		Expected Biovalidation Results ^b
Entrance	Exit	Entrance	Exit	End of Holding	End of Cooling ^a	End of Holding	End of Cooling ^a	
135.0	132.5	130.6	131.5	25.4	25.8	14.3	36.9	Negative
132.0	129.6	128.3	129.1	14.2	14.5	8.4	21.4	Negative
130.0	127.7	126.1	126.9	8.2	8.4	5.1	12.9	Negative/ Positive
124.0	122.1	122.4	122.8	2.4	2.4	2.1	3.9	Positive
120.0	118.2	118.6	118.9	1.0	1.0	0.9	1.6	Positive

^a End of cooling lethality represents the lethality of the entire Ohmic system (Ohmic heaters, hold tube, and cooling).

^b Biovalidation results are based on *Cl. sporogenes* kinetic data ($D_{250^{\circ}\text{F}} = 1.0$ min, z -value of 18°F) and spore concentration $10^5/\text{unit}$.

According to the NCFST/CAPPS workshop, the biovalidation process must be conducted using five levels of temperature. The highest temperature process must be performed in triplicate, assuming that it is the designated commercial process temperature. Process calculations based on mathematical modeling are illustrated in Table 29.6. It is worthwhile noting that these process temperatures are provided for demonstration purposes and cannot be used for commercial Ohmic process design. Food processors are advised to consult with a competent process authority before engaging in the manufacturing of Ohmically processed foods.

29.4.8 PROCESS BIOVALIDATION

Biovalidation tests for Ohmic systems will be conducted at five different temperature conditions as outlined by the NCFST/CAPPS workshop guidelines. The process temperatures will be based on recognized mathematical model predictions taking into account the desired target F_0 values and the measured minimum particle residence time. The target sterilization value (F_0) must be based on the heat resistance of the target organism (normally *Cl. sporogenes* PA-3679) in the product used in the biovalidation and the initial load of the organism. It is worthwhile noting that *Cl. sporogenes* PA-3679 is used as a surrogate for *Cl. botulinum* in the validation of low-acid foods products because it is nontoxic and nonpathogenic (Pflug, 2003).

A summary of the process temperatures obtained from the mathematical model calculations for conducting the biovalidation tests are shown in Table 29.7. The sterilization values were based on thermal death time (TDT) data of *Cl. sporogenes* PA-3679 ($D_{250^{\circ}\text{F}} = 1.0$ min, z -value of 18°F) in the food–alginate material to be used during the biovalidation tests. The TDT data ($D_{250} = 1.0$ min, z value = 18.0°F) must be determined for PA-3679 in the food–alginate matrix supplemented with 0.1% yeast extract, 0.1% glucose, and 0.02% FeSO_4 (Palaniappan and Sizer, 1997; Sastry and Barach, 2000; Sastry and Cornelius, 2002).

The product (mixed vegetable soup) will be prepared as established previously and pumped through the Ohmic line using the process temperatures as calculated above. It is critical to run the system several times before conducting the actual biovalidation tests to work out all detail, avoid disruptions, and gain confidence. This is because these tests are time consuming and expensive. It is necessary to estimate the minimum number of food–alginate particles needed to collect the required 299 particles for each temperature level as will be discussed later. The number of inoculated

TABLE 29.7**Process Temperatures Used for Biological Validation Tests of Ohmic Heating**

Hold Tube Temperatures (°C)		Minimum Particle	Microbial	Lethality
Entrance	Exit	Sterilization Value (min)	Reduction Factor	Calculated For
135.0	132.5	14.3	$14.3 \times D$	Hold tube exit
132.0	129.6	21.4	$21.4 \times D$	Whole system
130.0	127.7	12.9	$12.9 \times D$	Whole system
124.0	122.1	3.9	$3.9 \times D$	Whole system
120.0	118.2	1.6	$1.6 \times D$	Whole system

food–alginate particles to be processed must be significantly high to insure the collection of 299 intact particles following the product incubation period of 30 days at 30°C (Sastry and Cornelius, 2002). The preestablished number of inoculated food–alginate particles will be introduced into the flow stream and processed in the Ohmic system. The procedure will be repeated for all temperature levels. Each test must be designed to insure the collection of most of inoculated particles injected into the Ohmic system. The particles can be packaged in one or several containers depending on the aseptic filler connected to the Ohmic line. It is important to establish that the inoculated spores of PA-3679 can grow into the mixed vegetable soup; otherwise, the soup must be supplemented with a suitable growth media (Grischy et al., 1983; Sastry and Cornelius, 2002) at each of the five processing temperatures. For each processing temperature all containers filled with product will be marked and then incubated at 30°C. Additional details have been provided earlier.

It is worthwhile noting that one biovalidation run is made for the four lower temperatures (132.0°C, 130.0°C, 124.0°C, and 120.0°C) in Table 29.8, and three validation runs were made at the highest temperature (135.0°C), for a total of seven trial runs. The day-to-day variations and processing changes that might occur are not easily accounted for in the design of the process (i.e., fouling, operators, and start-up). They must be accounted for by conducting three validations at the scheduled process temperature.

Incubated containers are periodically observed for swelling. Swollen containers must be removed from the incubation room and opened. The presence of the test organism is normally verified and confirmed by the distinctive putrefactive odor characteristic of PA-3679 as well as microscopic

TABLE 29.8**Number of Samples (N) for Assurance of the Inclusion of the “Fastest” Particle in Ohmic Process Validation**

“Fastest” Particle Fraction (P)	Population Size (N)		
	Confidence of Collecting the “Fastest” Particle Fraction (C)		
	0.950	0.990	0.999
0.0050	598	919	1379
0.0100	299	459	688
0.0200	149	228	342

Source: Sastry, S.K. and Barach, J.T. Ohmic and inductive heating. *Journal of Food Science Supplement* 2000. 65:42–46. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

examination for typical rods. All of the processed packages are incubated for 28–30 days beyond the day of the last swollen package. When large packages (e.g., 55 gallon-bags) are used for Ohmic biovalidation, it is essential that the product is cooled as close as possible to the incubation temperature of 30°C to ensure temperature uniformity throughout the 55 gallon-bag.

The biovalidation must only be conducted after the identification of all of the critical factors associated with the process. According to the NCFST/CAPPS workshop, the critical process parameters must be carefully specified and the process shall be based on the identified critical factors and their limits. Consequently, the biovalidation tests are used to confirm the process as designed. As stated by the workshop there is only one fastest particle in the system. Therefore, the fastest particle under a certain set of specified conditions cannot be replicated. The reliability of the biological validation was based on the ability to identify the critical control factors, their limits, and the statistical reliability that is specified by the design of the biological validation test runs (Sastry, 1997).

29.4.9 STATISTICAL DESIGN

To date, there is no method by which the residence time of the fastest particle through the Ohmic system could be controlled. As a result, it is required to collect a significant portion of product for both residence time and biological validation tests to ensure the collected samples statistically include the “fastest” particle. The population of particles is assumed to have an unknown distribution. The distribution free-based equation below (Equation 29.6) was used to determine the sample size necessary for each of the tests (Digeronimo et al., 1997). For the measurement of residence times of N particles, the probability that at least one of the residence times is for the fastest particle is

$$C = 1 - (1 - P)^N \quad (29.6)$$

Solving for N will yield:

$$N = \frac{\ln(1 - C)}{\ln(1 - P)} \quad (29.7)$$

where N is the population size, C is the confidence of collecting the “fastest” particle fraction, and P is the “fastest” particle fraction. Therefore, a population of 299 particles is required for a 95% confidence of collecting the 1% of the fastest particles. It can be seen that the value N is dependent on C and P as listed in Table 29.8, which is calculated using Equations 29.6 and 29.7.

29.4.10 BIOVALIDATION DATA ANALYSIS

Before conducting the biovalidation residence time to ensure accuracy the Ohmic line must be determined. In the absence of residence time distribution data, process design can be based on laminar flow assumptions where the fastest particle velocity is twice that of the average particle. Also, this is critical to establish the timing to start the collection of the inoculated particles and estimate the number of inoculated particles to be introduced into the Ohmic line to ensure the collection of the required number particles based on the confidence interval and the particle fraction as in Table 29.9.

Once the particles are introduced into the Ohmic processing system, it is important to estimate when the fastest particle reached the filling machine and was collected in the package(s) for all seven runs as recommended by the CAPPS/NCFST workshop. All biovalidation packages are incubated at 95°F (35°C) for a minimum of 28–30 days and observed for swells at least once a day, provided that all packages from all runs. If swells are observed, the remaining biovalidation runs must continue to incubate for additional 28–30 days past the last observed swollen run.

TABLE 29.9
Microbiological Validation Test Results for a Typical Ohmic Processing Line

Hold Tube Exit Temperature (°C)	Swollen Containers	Subculturing/Results	Number of Cubes Recovered
135.0 (A)	Negative (–ve)	Yes/Negative (–ve)	>299
135.0 (B)	Negative (–ve)	Yes/Negative (–ve)	>299
135.0 (C)	Negative (–ve)	Yes/Negative (–ve)	>299
132.0	Negative (–ve)	Yes/Negative (–ve)	>299
130.0	Negative (–ve)	Yes/Negative (–ve)	>299
124.0	Positive (+ve)	NA	NA
120.0	Positive (+ve)	NA	NA

Following the 28–30 days incubation period beyond the last observed swollen bag, all nonswollen containers are aseptically opened and transferred to the enrichment media for *Cl. sporogenes* PA-3679 in test tubes. The tubes are incubated at 35°C (95°F) and checked daily for signs of growth (gas production and distinctive odor). This practice is referred to as sub-culturing. It is performed to verify and ensure that all PA-3679 spores are completely inactivated during the Ohmic treatment. Only the non-swollen packages are sub-cultured. Additionally, for large packages it is important that each of the nonswollen containers are emptied and examined carefully for isolated pockets of growth (Sastry and Cornelius, 2002). A temperature level is considered positive for PA-3679 growth once the presence of the organism is verified. All other packages in that level will be discarded. The results of the biovalidation must be in agreement with the model simulations; otherwise the process authority will have to investigate the results closely to explain the discrepancy between the model and the actual biovalidation data.

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30 Regulatory Issues

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30.1 INTRODUCTION

At one time, all processing of canned foods took place in retorts—closed vessels used for the thermal processing of foods under pressurized hot water/steam. They had the advantage of sterilizing both the hermetically sealed containers and their food contents at the same time. Retort technology improved on various aspects of this approach, creating variations on the theme of establishing a hot water/steam pressurized environment for processing.

For fluid foods, aseptic processing and packaging does away with the retort in favor of sterilizing the food first, then filling and sealing the food in a sterilized package. While this may seem at first more involved than retort operations, it adds considerable flexibility by allowing a larger variety of containers than retorting; creating a practically continuous process (most retort operations run in batch mode); and allowing different approaches to food sterilization than hot water/steam. Of course, of interest to the readers of this book is the use of Ohmic technology for effecting food sterilization.

In this chapter, the regulatory details of operating aseptic processes are discussed, pointing out details important to Ohmic heating. Its purpose is not to detail all the provisions of the regulations, but to indicate generally what is expected in the processing and handling of foods undergoing aseptic Ohmic treatment.

30.2 THE UNITED STATES FOOD AND DRUG ADMINISTRATION

The Food and Drug Administration (FDA) regulates medical devices, drugs, and most types of food. One might say that it has regulatory control over anything that interacts with the human body.

Its establishment followed decades of failed attempts to enact pure food and drug acts (Young, 2003). It was eight pages in a popular work of fiction describing in graphic detail the deplorable state of the Chicago's meatpacking industry in 1906 that appalled the American public, infuriated a United States President and motivated Congress to finally pass the needed legislation. *The Jungle* was Upton Sinclair's novel that depicted the dismal existence of the average American worker at the turn of the twentieth century. The repugnance of the working conditions described in those eight pages was enough to have the novel rejected by five publishers. The publisher Doubleday accepted the book only after one of their lawyers, sent to the meatpacking companies, verified the accuracy of Sinclair's description. After reading the novel, President Theodore Roosevelt sent inspectors who found evidence of the charges made in the book (Kantor, 1976). The result was the enactment of the Pure Food and Drug Act of 1906, establishing the FDA. Being a socialist journalist, Sinclair intended the novel as a general statement about labor, but the plight of the worker—the primary subject of the novel—was largely ignored by the public. In spite of the positive impact he had on food safety and hygiene, Sinclair was to later lament “I aimed at the public's heart, and by accident I hit it in the stomach” (Kantor, 1976).

While the establishment of the FDA resulted from the Pure Food and Drug Act of 1906, the modern foundation of FDA regulatory control is the Food, Drug and Cosmetic (FD&C) Act of 1938 (Anonymous, 2010). This was a replacement for the 1906 act that, in the decades following its enactment, was found to not extend far enough. Deaths from a sulfanilamide elixir, total blindness from an eyelash dye, slow and painful deaths from a radium-based tonic and deceptively packaged food, none of which fell under the 1906 act, prompted the development and enactment of the FD&C Act.

The growth of the FDA since the FD&C Act has been in response to the various food safety, drug and medical device-related issues that were encountered since that time. In the 1970s, deaths and illnesses from botulism that were the result of inadequate processing of food that supports the growth of the organism *Clostridium botulinum*, led to regulations specific to the processing of such foods. It is those regulations that are the subject of this chapter.

The FD&C Act appears in the United States Code (USC) under Title 21 that covers food and drugs. Coincidentally, it is the same title number that food and drugs come under in the Code of Federal Regulations (CFR). The USC is the compilation of laws enacted by Congress, while the CFR is the compilation of rules and regulations that are promulgated by the agencies of the executive branch of United States Government that are given jurisdiction over a specific part of the USC. Enactment and promulgation are synonymous in that they indicate official recognition. Enactment, however, is applied to acts of Congress and promulgation to rules and regulations of government agencies. Therefore, though they are not Acts of Congress, and not generally referred to as laws, rules, and regulations are nevertheless enforceable by virtue of the USC. At various points the CFR references the USC (by way of the FD&C Act) mainly to remind the reader that while regulations in the CFR must be followed, they do not relieve the user of any applicable sections existing in the FD&C Act.

Although the FDA has oversight over most types of food, other governmental agencies provide food-related oversight as well. The U.S. Department of Commerce oversees imported foods and the Environmental Protection Agency (EPA) oversees the use of chemicals in food processing such as sterilants that may be used on food contact surfaces. The U.S. Department of Agriculture (USDA) has oversight over meat products and food products that contain 3% or more raw meat, or 2% or more cooked meat. What remains are seafood and nonmeat products that fall under FDA jurisdiction. However, not *all* food comes under FDA jurisdiction; only food that is distributed in interstate commerce. What is produced for sale within a state comes under that state's guidelines for food handling. However, most states have adopted federal guidelines presented in FDA's Food Code (Anonymous, 2009). The Food Code is periodically updated, with the last update in 2009 and gives the most recent recommendations on proper food handling.

Some examples of FDA-regulated foods are given in Table 30.1. For the purpose of this chapter, the most important of these foods are canned foods, more formally known as low acid canned foods

TABLE 30.1
Examples of FDA-Regulated Foods

Food and food additives for man or animals
Dietary supplements and dietary ingredients
Infant formula
Beverages (including bottled water)
Fruits and vegetables
Fish and seafood
Dairy products and shell eggs
Raw agricultural commodities for use as food or components of food
Canned foods
Live food animals
Bakery goods, snack food, and candy

(LACF) and also known as, more inclusively, low acid shelf stable foods. This latter designation takes into account containers other than cans.

One last remark on the FDA—some may view the FDA, or other agencies of the federal government, as an impenetrable edifice. However, being an agency of the federal government, the FDA is open to direct access by the public at no charge. This, of course, includes food processors. If a novel food process is being developed and questions arise as to how regulations impact such a process, it is strongly encouraged that the processor contacts the FDA as early in the development as practical. Early and continued contact with the FDA allows the processor to understand what is expected of the process which is not always apparent. A misinterpretation of the regulations or an oversight can be caught early, preventing costly delays or equipment modifications.

30.3 CLOSTRIDIUM BOTULINUM, LOW ACID CANNED FOODS AND COMMERCIAL STERILITY

C. botulinum is a Gram-positive, nonmotile bacteria that is also a strict anaerobe. In response to environments that cannot support its growth, it forms a spore that is very resistant to inactivation. *C. botulinum* spores are common in cultivated and forest soils, on shores, and in the beds of streams, lakes, and coastal waters. It can be found in the gills and viscera of crabs and other shellfish and in the intestinal tracts of fish, birds, and animals (Dodds, 1992). Perhaps ironically, the spore itself is not harmful. However, if exposed to the proper environment, it germinates and grows, producing a toxin, botulinum neurotoxin (BoNT). BoNT, as part of its name implies, is toxic to the nervous system, impeding and blocking signal transport between nerves resulting in paralysis and eventually death. The potency of this toxin cannot be underestimated. In purified form its lethal dose in humans is measured in nanograms (Gill, 1982).

Foods described as LACF, if not processed correctly, can lead to the growth of the organism *C. botulinum*. Table 30.2 gives all the requirements that must be met for a food to be considered

TABLE 30.2
Criteria for the Designation of Low-Acid Canned Foods

Non-tomato foods having a pH greater than 4.6
Tomato foods having a pH greater than or equal to 4.7
Foods having a water activity greater than 0.85
Foods stored at room temperature
Foods packaged in a hermetically sealed container

TABLE 30.3
Examples of Non-LACF Foods

Acid foods
Fermented foods
Certain jams, jellies, and preserves
Alcoholic beverages
Carbonated beverages
Foods requiring refrigeration

LACF. The reason for the specification of “low acid” in the LACF name is that it is the pH of the environment that determines whether *C. botulinum* grows or not. It is not the only criterion by which LACF is defined. It should be noted that the definition includes how the food is packaged and stored in addition to the levels of intrinsic food properties of pH and water activity. Table 30.3 shows some examples of foods that do not fall under the LACF definition.

The modern era of FDA oversight on LACF processing occurred as a result of two incidences of BoNT poisoning in 1971 causing a prolonged illness in one victim and death in another attributed to canned potato soup normally eaten without being heated (Anonymous, 2003). It was later determined that the soup was underprocessed. Regulations targeting LACF processing were promulgated shortly after that time. The fundamental goal of the regulations was to ensure that any process that produces LACF product would do so as to render the food product commercially sterile.

Commercial sterility occurs when a food is made free of viable forms of microorganisms having public health significance, as well as any microorganisms of nonhealth significance capable of reproducing in the food under normal nonrefrigerated conditions of storage and distribution. This definition appears in the 21 CFR 113.3(e) (Anonymous, 2008) Nevertheless, commercially sterile foods are not necessarily bacterially sterile.

30.4 THE REGULATIONS I: GENERAL LACF PROCESSING

From the Government Printing Office’s Code of Federal Regulations (CFR) search page (Anonymous, 2008), “The Code of Federal Regulations (CFR) is the codification of the general and permanent rules published in the Federal Register by the executive departments and agencies of the Federal Government. It is divided into 50 titles that represent broad areas subject to Federal regulation.” Within these 50 titles is Title 21 that deals with food for human consumption and drugs, with parts 100 through 199 dealing directly with food. For low acid canned foods, parts 108, 113, 114 apply. For Ohmic heating, parts 170, 174, and 180, which cover food additives, may also apply due to the contact between electrodes and foods. The entire code is available in print or electronic form either the Government Printing Office (U.S. Government Bookstore, 710 North Capitol Street N.W., Washington, DC or online at <http://www.gpo.gov>) or in searchable electronic form at <http://www.gpoaccess.gov/cfr/index.html>.

30.4.1 21 CFR 108: EMERGENCY PERMIT AND CONTROL

Part 108 deals with administration of the LACF regulatory program. Subpart A comes into effect when an LACF processor does not meet the mandatory conditions for producing safe foods (i.e., foods that do not pose an imminent hazard to health). It states that such a processor may continue processing but only with a permit issued by the FDA, with the permit stipulating those conditions under which processing can continue. Other sections in this subpart discuss the details of permit issuance, revocation, suspension, and reinstatement. In general, a permit is not necessary when a processor operates under the mandatory conditions for producing safe foods.

Subpart B appropriately discusses the specific requirements for a processor to avoid needing a permit for processing or, if a permit is necessary, for processing in compliance with it. Acidified foods are covered first. Such foods have their pH lowered to a level below which *C. botulinum* spores will not germinate. Even so, processors are still required to register their company with the FDA, as well as file their process (more about processor registration and process filing below).

Probably the best-known section of Title 21 is in subpart B; that being 108.35, the thermal processing of low-acid foods in hermetically sealed containers. All processors of such foods must be registered with the FDA and their processes filed as stipulated in this section. The easiest way to do this is on-line. The starting point is the FDA LACF web page at: <http://www.cfsan.fda.gov/~comm/lacf-toc.html>.

On this page, interested parties will find the links to the LACF regulations, filing forms, and the link to initiate on-line filing. This link will take the user to an information page with an email address for the LACF program at FDA. Processors wishing to file on-line must make an email request for a free account to the address given on the information page. The reply will include a username, password, and instruction on how to proceed.

Once filed, the FDA will conduct a review of the process to determine if, under the operating conditions presented, the process is capable of producing a safe product. If the FDA does not consider the need for the processor to supply additional information, it will accept the filing. *This is not an approval.* The FDA does *not* approve processes. The actual responsibility to produce safe food using the process belongs to the processor. This is a subtle point and often times the acceptance of a filing is mistakenly referred to as an approval of the process when in fact it is simply permission to process until such time that the FDA may desire additional information.

The remainder of 108.35 includes processes deviations and their reporting to the FDA, the keeping of records, compliance with State regulations, and imports.

30.4.2 21 CFR 113: THERMALLY PROCESSED LOW-ACID FOODS PACKAGED IN HERMETICALLY SEALED CONTAINERS

In this part the details of processing are covered. Retorts have a long history of use in LACF processing and appropriately most of Part 113 covers the use of such vessels for processing. This includes process monitoring and control, retort configuration and critical factors. For aseptic processes (21 CFR 113.40 g), additional discussion covers regeneration (the recovery of process heat to preheat incoming food), flow diversion systems, holding tubes, and other items unique to aseptic processing. The remainder of Part 113 covers containers, production and process controls, process establishment, deviations in processing, and records and reports.

With so much detail involved in LACF processing, Part 113 stipulates that “scheduled processes for low-acid foods shall be established by qualified persons having expert knowledge of thermal processing requirements for low-acid foods in hermetically sealed containers and having adequate facilities for making such determinations.” Large food production companies usually have an in-house authority for such a task. Smaller companies hire process authority consultants. The question may arise that if process authorities are used to establish a process, why is it necessary to additionally submit the process to the FDA for review? The reason for this is explained in Mulvaney et al. (1978). In 1973 it was found that LACF processors were using either questionable processes or processes not established by a qualified thermal processing authority. This initiated the need for filing an established process for review by the FDA to identify substandard processes. Yet, the regulations do not provide guidance on what constitutes a process authority or how to choose one. In general, though, they must be conversant with all aspects of LACF processing and their experience is a good guide.

30.4.3 21 CFR 114: ACIDIFIED FOODS

Acid foods have a natural pH less than or equal to 4.6 and, as discussed previously, do not fall under these regulations. It makes sense that adding acid to a low-acid food helps avoid the usual issues it

has vis-à-vis *C. botulinum*. These types of foods are *acidified* by having an acidifying component added to achieve the same low pH. However, such foods do not totally escape the low-acid regulations, having this special section. The reason is to ensure that the important performance criterion of having a finished pH of 4.6 or less is met. Indeed, most of Part 114 covers its measurement and discusses as well the importance of measuring the pH as a final, equilibrium value.

When establishing an acidified food process the acidified food, according to 21 CFR 114.80(a)(1), “shall be thermally processed to an extent that is sufficient to destroy the vegetative cells of microorganisms of public health significance and those of non-health significance capable of reproducing in the food under the conditions in which the food is stored, distributed, retailed and held by the user. Permitted preservatives may be used to inhibit reproduction of microorganisms of non-health significance (in lieu of thermal processing).”

30.4.4 21 CFR 170, 174, AND 180: FOOD ADDITIVES

Food additives are of two types: direct and indirect. Direct are those additives that have an intended effect on food. Indirect are those additives whose presence in foods is not intended. Indirect additives usually enter food through contact with packaging or processing equipment. In the other parts of this regulation not covered here there is detailed information on a variety of additives, both indirect and direct.

Specifically, 170.39 discusses the threshold of regulation for substances used in any food-contact materials. Four criteria are used to assess whether an additive falls under the threshold of regulation. The first is that the additive is not a carcinogen in humans or animals and must not contain a carcinogenic impurity. The second states that it presents no health or safety concerns either because it is regulated within an existing exposure limit or that it results in exposure levels of 1.5 µg/person/day (this quantity based on a 0.5 parts per billion concentration in a 3000 g daily intake of food). The third is that the substance does not interact with the food and the fourth stipulates it has no adverse impact on the environment. At any time, however, the FDA reserves the right not to grant an exemption for additives when data are available to show that the additive is a public health risk.

More information for seeking exemption from the food additive regulations can be obtained by contacting the FDA’s Office of Food Additive Safety (previously the Office of Premarket Approval) (HFS-200), 5100 Paint Branch Parkway, College Park, MD 20740.

Part 174 covers unspecified indirect additives with the following restrictions. The first is that for those substances for which no regulated level of exposure exists, no more of the additive is allowed into the food than the minimum required to accomplish the intended effect.

The other sections not mentioned here are additive specific and may impact Ohmic heating only insofar as the food being processed.

30.4.5 21 CFR 11: ELECTRONIC RECORDS; ELECTRONIC SIGNATURES

The relatively short Part 11 of 21 CFR covers electronic records and electronic signatures. Any time an automated system is used to monitor a critical factor, record it electronically, and not print it as a permanent record, it has created an electronic record and must be in compliance with part 11. It is recommended that processors become familiar with this part as well as with Guide 43 L from the Grocery Manufacturers Association/Food Products Association (Anonymous, 2002). This guide describes the best practices to validate modern computerized processing systems.

30.5 THE REGULATIONS II: IMPACT ON OHMIC HEATING

The development of any novel LACF process benefits from early and continued contact with the FDA. “Early” means during development. In this way, FDA officials become familiar with the

process and can guide the processor on issues of public health significance. There have been cases where novel processes were conceived and developed only to have run aground due to an overlooked food safety issue. Because the FDA mandate is to protect the public health, such an issue must be dealt with even if its impact on the processor is onerous.

30.5.1 GENERAL ESTABLISHMENT OF A NOVEL PROCESS

The FDA is interested in four aspects of a novel process (Larkin and Spinak, 1996): equipment design, production specification, process design, and process validation. The equipment design should be complete, including details such as validation procedures for software-based control systems and methods for the production of process records. The product specification is a complete description of the product, with emphasis on critical parameters—those parameters that affect the ability of the Ohmic system to achieve consistent commercial sterility of the product. It may include any Ohmic-related and thermal attributes as necessary. Process design is the description of critical processing conditions, how these conditions were established, and how changes in product formulation affect them. Lastly, process validation is the physical demonstration of the process that demonstrates its effectiveness and consistency.

30.5.2 ADDITIVES

In an Ohmic aseptic process the primary concern is delivering the proper treatment to render food safe. A secondary concern is the contact between food and electrodes. Electrochemical reactions at the electrode cause metal ions to migrate into food (e.g., Samaranayake and Sastry, 2005), thus making the ions indirect additives. Although the food additive regulations do not address this type of migration directly, language included in section 170.39 addresses general migration from materials in food packaging or processing. FDA's Office of Food Additive Safety needs to be consulted concerning the Ohmic electrodes and food to be processed. A quantitative assessment of the interaction between the food and electrodes needs to be known before the Office of Food Additive Safety can determine if the contact poses a food additive issue.

30.5.3 PARTICULATES

The LACF regulations have one objective—that when LACF products are produced, all parts of the food are brought to a state of commercial sterility. When a food is homogenous, achieving the goal is straightforward in most cases (microwave-based processing of solid foods being an exception). Complications set in when the food is nonhomogeneous. In aseptic processes this means particulates suspended in a liquid food medium.

From a practical point of view, one could say that a particulate is any solid that can be discerned in a liquid food. However, from a regulatory point of view, a particulate is something that would have heat-transfer properties differing from those of the surrounding food medium. It is therefore possible to have visible particulates without having the food considered particulate containing in nature. This could be due either to consistent heat-transfer properties between the particulates and the food medium or because the particulates are thin or small enough such that any difference in heat-transfer properties is minimized by the small distance across which heat is transferred. Regardless, the FDA must see that data support a conclusion of consistent heat-transfer properties between medium and particulate.

The challenges of aseptic processing of particulates in general have been previously discussed (e.g., Larkin and Spinak, 1996; Sastry and Cornelius, 2002). In Ohmic heating, particulates present the double challenge of potentially having different thermal *and* electrical properties. The goal for process establishment is, of course, the same—insuring that the slowest heating part or particulate of the food is adequately heated. Therefore, when establishing this process, the FDA

must see an adequate assessment indicative of complete processing of the food that includes both heat transfer to particulates and an assessment of the relative heating based on electrical considerations.

30.6 SUMMARY

The FDA is charged with protecting the public health. It has promulgated and continues to promulgate regulations to do so. Where food processes are concerned, these cannot cover every detail of every possible food process without becoming unwieldy and unenforceable. They, therefore, cover in broad areas what is expected of processing for the production of safe foods. This allows the development of novel food processes but does put the burden of proof on processors to show that such processes succeed in the production of safe foods.

To aid the processor, the FDA strongly encourages contact when there are any questions concerning product or process. When the process is novel, processor contact with the FDA as early as practical is strongly encouraged and that contact is kept throughout development. This helps eliminate unforeseen issues and keeps FDA personnel abreast of emerging technology.

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OHMIC HEATING *in* FOOD PROCESSING

Ohmic heating provides rapid and uniform heating, resulting in less thermal damage than conventional heating and allowing manufacturers to obtain high-quality products with minimum sensorial, nutritional, and structural changes. **Ohmic Heating in Food Processing** covers several aspects of Ohmic heating: science and engineering, chemistry and physics, biochemistry and nutrition, quality and safety, and development and technology, both basic and applied. It describes the importance of Ohmic technology and how to implement it in practice, addressing basic theory, principles, and applications.

Divided into nine sections, this volume covers the basics of Ohmic heating, including a historic overview and fundamental principles; electrical conductivity, its importance, factors that influence it, and data modeling; biological effects of electricity on foods and food components, including microorganisms, enzymes, proteins, carbohydrates, and fats; and Ohmic heating behavior and design parameters. The book also deals with issues in Ohmic heating equipment, Ohmic heating modeling issues, and process validation issues.

The authors discuss various applications of Ohmic heating applied to different classes of foods, such as muscle foods (meat, poultry, and fish), dairy products, fruits, and vegetables. They also examine commercially successful applications of food products processed by Ohmic heating and considers applications of Ohmic heating where preservation is not the main focus, for example, blanching, Ohmic thawing, and the potential for Ohmic heating for long-duration space missions.



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