ELSEVIER

Trends in Food Science & Technology 21 (2010) 436–441

TRENDS IN
FOOD SCIENCE
& TECHNOLOGY

Review

Ohmic heating – a review

Marcos Camargo Knirsch[a,*], Carolina Alves dos Santos[a], António Augusto Martins de Oliveira Soares Vicente[b] and Thereza Christina Vessoni Penna[a]

[a]Department of Biochemical and Pharmaceutical Technology, School of Pharmaceutical Sciences, University of São Paulo, Av. Professor Lineu Prestes, 580, Bloco 16, 05508-900 São Paulo, São Paulo, Brazil (Tel.: +55 11 30913710; fax: +55 11 30912376. ; e-mails: marcos.knirsch@usp.br; mcknirsch@yahoo.com)

[b]University of Minho, Braga, Portugal – Centro de Engenharia Biológica, Campus de Gualtar, 4710-057 Braga, Portugal

Ohmic heating (OH) is defined as a process wherein electric current is passed through materials with the primary purpose of heating them. In OH there is no need to transfer heat through solid–liquid interfaces or inside solid particles once the energy is dissipated directly into the foods. A large number of actual and potential applications exist for OH, including blanching, evaporation, dehydration, fermentation, extraction, sterilization, pasteurization and heating of foods to serving temperature, including in the military field or long-duration space missions. Additionally to heating, research data suggests that the applied electric field under OH causes electroporation of cell membranes.

Introduction

Inactivation of microorganisms is important in many industrial applications and novel low-energy or energy-efficient methods of inactivation continue to attract interest (Palaniappan & Sastry, 1992; Piette, Dostie, & Ramaswamy, 2001a). Concerning product safety and quality management, microbial inactivation is a key parameter to be addressed in food production processes. The presence of undesired or high numbers of certain microorganisms may cause product deterioration (*e.g.* substance degradation), quality loss (*e.g.* appearance changes, off-odors, off-taste, color deterioration, etc) and/or health problems (*e.g.* diseases and/or illnesses). Inadequate cooking, for example, is thought to be the major cause of *Salmonella* spp. outbreaks (Smith *et al.*, 2008; USA-CDC, 2008).

When materials contain sufficient water and electrolytes to allow the passage of electric current, Ohmic Heating (OH) can be used to generate heat within the product (Imai, Uemura, Ishida, Yoshizaki, & Noguchi, 1995). OH (also referred to as Joule heating, electroheating, and electroconductive heating) is defined as a process wherein electric current (usually alternating) is passed through materials with the primary purpose of heating them (Vicente, Castro, & Teixeira, 2006). The heating occurs in the form of internal energy transformation (from electric to thermal) within the material (Sastry & Barach, 2000). Therefore, OH can be seen as an internal thermal energy generation technology, and not only as a thermal energy transfer, meaning that it does not depend on heat transfer either through a solid–liquid interface or inside a solid in a two-phase system.

Ohmic processing enables to heat materials at extremely rapid rates (in general, from a few seconds to a few minutes) (Sastry, 2005). It also enables, under certain circumstances, large particulates and carrier fluids to heat at comparable rates, thus making it possible to use High Temperature Short Time (HTST) and Ultrahigh Temperature (UHT) techniques on solids or suspended materials (Imai *et al.*, 1995), increasing the final product quality and adding value to products (Castro, Teixeira, & Vicente, 2003; Kim *et al.*, 1996; Parrott, 1992; Tucker, 2004; Vicente *et al.*, 2006). This very desirable scenario is hardly achieved using conventional heating (Lima, Heskitt, Burianek, Nokes, & Sastry, 1999). Thereby the aseptic processing of fluids containing particulates and fluids of high viscosity are considered the most promising applications of OH in the food industry (Palaniappan & Sastry, 2002; Rice, 1995; Wang, Kuo, Kuo-Huang, & Wu, 2001).

OH presents a large number of actual and potential future applications, including its use in blanching, evaporation, dehydration, fermentation, extraction (USA-FDA, 2000), sterilization, pasteurization and heating of foods to

---

* Corresponding author.

0924-2244/$ - see front matter
doi:10.1016/j.tifs.2010.06.003

serving temperature in the military field or long-duration space missions (Sastry *et al.*, 2009). Still most applications are waiting for commercial exploitation (Sastry, 2005).

Food processing – electric conductivity, the critical parameter

Since the main critical factor in thermal processes is the thermal history and location of the "cold spot", locating cold zones during OH requires special consideration as the current knowledge of conventional heating cannot be extrapolated to OH technology (USA-FDA, 2000). In a non homogeneous material, such as soups containing slices of solid foods, the electrical conductivity (σ) of the particles and its relation to the fluid conductivity is pointed as a critical parameter to the understanding of the particles' heating rate under OH (Palaniappan & Sastry, 1991b). Proper electric conductance management is essential to successfully apply OH (Biss, Coombes, & Skudder, 1989; Castro, Teixeira, Salengke, Sastry, & Vicente, 2004; Fryer & Zhang, 1993; Wang *et al.*, 2001).

The heating rate of particles in a fluid depends on: (i) the relative conductivities of the system's phases and (ii) the relative volume of those phases (Sarang, Sastry, Gaines, Yang, & Dunne, 2007). Low conductivity solid particles, comparatively to the fluid conductivity, tend to lag behind the fluid at low concentrations related to the volume of the fluid. However, in conditions where the concentration of the particles is high, those same low conductivity particles may heat faster than the surrounding fluid. So, the phenomenon of particle-lagging or particle-leading depends on the significance of particle resistance to the overall circuit resistance (Sastry & Palaniappan, 1992). This phenomenon occurs because, with the increase of the particles' concentration, the electric current path through the fluid becomes more tortuous, forcing a greater percentage of the current to flow through the particles. This can result in higher energy generation rates within the particles and consequently in a greater relative particle heating rate (Sarang *et al.*, 2007; Sastry & Palaniappan, 1992). This fact indicates that it may be possible to adjust the heating pattern of solid–fluid systems by adjusting the overall influence of particles' resistance in the system through setting the particles concentration in the fluid.

The electric conductivity of some systems may also be altered to achieve the ideal OH situation, when the conductivity of the particles is equal to the surrounding fluid (Wang & Sastry, 1993a). However, as pointed by Halden, De Awis, and Fryer (1990) it is unlikely that the exact same heating rate can be achieved throughout the process, even though the thermal difference, in practical terms, may be too small to be significant.

In fact, the electric conductivity is a function of the structure of the material and often changes by heating (cooking); however in some foods, the overall heating effect might be too little to alter the pattern of electrical conductivity (Pongviratchai & Park, 2007). There are also critical σ values below 0.01 S/m and above 10 S/m where OH is not applicable. This is because very large voltages or very large amperage values would be needed to generate the amount of heat required raising temperature substantially by the Joule effect, in case of very low or very large σ values, respectively (Piette *et al.*, 2004; Piette, Dostie, & Ramaswamy, 2001b).

Palaniappan and Sastry (1991a) reported that the infiltration of a salt solution might increase the conductance of vegetables while, in contrast, the leaching out of ions from vegetable tissue during immersion in water may decrease conductance. Halden *et al.* (1990) monitored conductance during the blanching of vegetables and suggested that the destruction of cell walls released cytoplasm contents thus changing the conductance value. Later, Wang and Sastry (1993a) suggested that the infiltration of salt solution to improve the conductance of vegetable tissue.

Increasing the electrolytic content within foods to increase electrical conductivity may be accomplished by salt infusion *via* soaking or blanching of solids in salt solution. This may be used as a pretreatment for OH for particulate foods to obtain uniform heat treatment, if the composition and other properties of the food are not greatly affected (Palaniappan & Sastry, 1991a; Wang & Sastry, 1993a, 1993b). However, a low-temperature soaking method has the disadvantage of being time consuming (Sarang *et al.*, 2007).

The possibility to alter the electrical conductivity of solid foods by blanching pretreatment has been studied by Sarang *et al.* (2007). In this study the solid constituents of chicken chow mein (chicken, celery, bean sprouts, mushroom, water chestnuts) have been blanched in a highly conductive soy sauce at 100 °C for different lengths of time to adjust their electrical conductivity to that of the chow mein sauce; the modifications in the electric conductivity of the chicken and vegetables were determined. As the vegetable tissue is heated, structural changes like cell wall breakdown, tissue damage, increase of mobile moisture, and softening occur, affecting the electrical conductivity (Wang & Sastry, 1997). Thus heating causes more mobile moisture, increasing ionic mobility, which in turn increases the electrical conductivity (Sarang *et al.*, 2007). It was also observed that there was a time limit (5–6 min) beyond which the blanching of mushroom for further processing may cause shrinkage and loss of porosity of the material and therefore causing a decrease of its electric conductivity. The blanched chicken meat did not show a significant increase in conductivity: this fact is attributed to the chicken meat behavior that typically shrinks and becomes less permeable after blanching as opposed to most vegetables tissue, which turns soft. In fact, while the ionic content is increased in chicken after blanching, the overall ionic mobility may be reduced due to low permeability. These opposed effects may explain why only small increases in the electrical conductivity could be observed for chicken meat (Sarang *et al.*, 2007).

Therefore the material infrastructure may also interfere in the electric conductance. Wang *et al.* (2001) have demonstrated that the conductance of bamboo, sugarcane, lettuce and mustard can differ if it is measured along the stem or across it. Wang *et al.* (2001) argue that the difference in electric conductance measurements from the same material should, therefore, be explained by tissue infrastructure rather than chemical composition. It was observed that both the orientation of vascular bundles and the shape of parenchyma cells can influence the electric conductance in vegetables (Wang *et al.*, 2001).

The electrical conductance readings of the same vegetables also vary pronouncedly in the literature. For example, the electric conductance of potato can be 0.037 S/m (Kim *et al.*, 1996), 0.06 S/m (De Alwis, Halden, & Fryer, 1989), or 0.32 S/m (Palaniappan & Sastry, 1991a), and carrot can be 0.041 S/m (Kim *et al.*, 1996) or 0.13 S/m (Palaniappan & Sastry, 1991a). As mentioned before, other than the difference in the composition of the test samples and the methodology used, the direction for taking measurements may also be a contributing factor to the variation (Wang *et al.*, 2001).

Amongst the principal causes of electrical conductivity changes in foods during OH, the destabilization of cellular membranes is pointed to be the main responsible effect for the reduction of the system's impedance (An & King, 2007; Imai *et al.*, 1995; Lebovka, Praporscic, Ghnimi, & Vorobiev, 2005; Pongviratchai & Park, 2007), but it is also affected by cell rupture, cell electroporation, tissue shrinkage, phase change, dehydration, starch gelatinization, salt concentration and mobility, moist mobility, pH value and the presence of fat or other non-conducting substances (Piette *et al.*, 2004; Pongviratchai & Park, 2007), among other factors.

Microbial inactivation

The principal mechanisms of microbial inactivation in OH are thermal in nature. Recent research indicates that OH may present mild non-thermal cellular damage due to the presence of the electric field (Cho, Yousef, & Sastry, 1999; Pereira, Martins, Mateus, Teixeira, & Vicente, 2007; Sun *et al.*, 2008). The principal reason for the additional effect of ohmic treatment may be its low frequency (usually 50–60 Hz), which allows cell walls to build up charges and form pores (USA-FDA, 2000). As a main consequence of this effect, the D value observed for the microbial inactivation under ohmic heating is reduced when compared to traditional heating methods. This reduction has been observed for *Bacillus licheniformis* and *Escherichia coli* (Pereira *et al.*, 2007), *Bacillus subtilis* (Cho *et al.*, 1999), *Streptococcus thermophilus* (Sun *et al.*, 2008) and *Byssochlamys fulva* (Castro, 2007).

Little research has been performed on the influence of ohmic heating on microbial activity and inactivation. The thermal treatment required for microbial inactivation in biomaterials and foods could be potentially reduced if there exist any sublethal injury or additional lethal effect due to electric current (Palaniappan & Sastry, 1992).

There have been no reports of particular resistant microorganisms or pathogen strains with unique resistance to the technology, the most resistant pathogens would likely be the same as those for thermal processes (USA-FDA, 2000).

Pereira *et al.* (2007) have reported lower D and z values for the inactivation of *E. coli* and *B. licheniformis* when submitted to ohmic heating. In this research, comparing conventional against ohmic heating, the thermal history of the samples analyzed was adjusted to match. The D values observed for *E. coli* at 65 °C were 3.5 ± 0.2 and 0.86 min for conventional and ohmic process respectively. The z values were also reported as 23.1° and 8.4 °C respectively. The observed results indicate that the electric current may have affected the microbial death rate (Pereira *et al.*, 2007). Similar observations were obtained in the same study for the spore inactivation of *B. licheniformis*. Considering both microorganisms strain, ohmic heating presented a lower D value. This fact indicates that an additional non-thermal lethal effect occurred under ohmic heating, due to the presence and effects of the electric current over vegetative cells of *E. coli* and bacterial spores of *B. licheniformis* (Pereira *et al.*, 2007).

In the study, performed by Cho *et al.* (1999) on the *B. subtilis* and *Bacillus atrophaeus* inactivation kinetics by conventional moist heating and ohmic heating, is possible to observe that the application of an electric field leads to lower thermal inactivation time, for the same temperature of treatment; per example, the D value at $T = 92.3$ °C was reduced by 1 min for ohmic heating when compared to conventional heating by water circulation. It is possible, therefore, to infer that the microbial inactivation was affected by the incident electric field in the medium during the heating process.

However, Palaniappan and Sastry (1992) found no difference between the effects of ohmic and conventional heat treatment on the death kinetics of yeast (*Zygosaccharomyces bailli*), under identical heating histories. In some cases, however, a mild electrical pretreatment decreased the subsequent inactivation requirements, for *E. coli*. The authors observed only slightly lower D values for the inactivation of *Zygosaccharomyces bailii* and *E. coli* when ohmic heating was applied at temperatures lower than 56 °C. Although these D values were lower when compared to conventional heating, a t-test comparison at 95% confidence level showed no significant statistical difference between treatments (Palaniappan & Sastry, 1992).

Milk viable aerobes and *S. thermophilus* inactivation have been accessed by Sun *et al.* (2008). According to the authors the observed results demonstrated that ohmic heating causes higher microbial death than the conventional heating process. In this study, the final microbial count and the calculated D values for ohmic heating were significantly lower than those acquired from conventional heating, under the same temperature history conditions.

Therefore, it was pointed that ohmic heating caused a thermal lethal effect and an additional non-thermal lethal effect on the studied microorganisms (Sun *et al.*, 2008). According to Sun *et al.* (2008) the inactivation effect of electricity is significant compared to that of heat and was shown to be related to the electrical voltage and frequency.

Yoon, Lee, Kim, and Lee (2002) have investigated the effect of ohmic heating on the structure and permeability of cell membrane of yeast cells (*Saccharomyces cerevisiae*). Under similar time–temperature history, for both conventional and ohmic heating, the authors have observed that little differences between processes could be observed under 50 °C but the difference of yeast cell destruction rate under ohmic heating became much pronounced at 70–80 °C (Yoon *et al.*, 2002).

Electroporation effect

Additionally to the heating promotion, research data strongly suggests that the applied electric field under OH causes electroporation of cell membranes. The cell electroporation is defined as the formation of pores in cell membranes due to the presence of an electric field and as consequence, the permeability of the membrane is enhanced and material diffusion throughout the membrane is achieved by electro-osmosis (An & King, 2007; Coster & Zimmermann, 1975; Lima & Sastry, 1999). It is assumed that the electric breakdown or electroporation mechanism is dominant for the non-thermal effects of OH (An & King, 2007; Kulshrestha & Sastry, 2003; Sensoy & Sastry, 2004).

Yoon *et al.* (2002) observed that under OH the electric field appeared to have both direct and indirect effect on the cell wall, and intracellular materials were exuded to the culture medium. The exudates seemed to be composed of amino acids, protein, nucleic acids, coenzymes, and related material (Yoon *et al.*, 2002). It is stated that, below 50 °C, similar concentrations of exuded material were detected in the yeast supernatant, under conventional or OH. However, at temperatures above 50 °C, the concentration of exuded materials from the ohmic heated groups were higher than those from conventional groups ($p < 0.01$) and that the rate of protein exuded per unit temperature increase was found to be significantly higher ($p < 0.01$) with OH than with 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 within OH might have increased the rate of electroporation, thereby leading to excess exudation and cell death. It was also observed that the amount of exuded protein increased significantly as the electric field increased from 10 to 20 V/cm. Spectroscopic analysis has shown that for OH at 20 V/cm the absorbance at 260 nm typically attributed to nucleic acids was 2-fold ($p < 0.01$) and the total protein content was 3-fold higher ($p < 0.01$) when compared with that at 15 V/cm (Yoon *et al.*, 2002).

When applied at sublethal temperatures, the electroporation effect caused by the OH method has demonstrated the potential to benefit fermentative processes. The application of OH was studied for the fermentation of *Lactobacillus acidophilus* by Cho, Yousef, and Sastry (1996) and also by Loghavi, Sastry, and Yousef (2008, 2009). In Cho *et al.*'s (1996) study, the fermentative process temperature control was performed by conventional heating (water bath) and by OH (at constant voltage values of 15 V or 40 V). The processes were conducted at different temperatures (30°, 35° and 40 °C). It was observed that the incidence of electric field in the process may cause membrane electroporation provoking faster and more efficient nutrient transport to the interior of the cell, thus reducing the lag phase of the fermentation. On later fermentative stages, however, OH has demonstrated to cause productivity decrease. This decrease may also be related to the electroporation effect which possibly allows the transport of metabolites to the interior of the cell and consequently inhibits the fermentative process (Cho *et al.*, 1996; USA-FDA, 2000).

Conclusions

OH is an emerging technology with large number of actual and future applications. The possibilities for OH includes blanching, evaporation, dehydration, fermentation, extraction, sterilization, pasteurization and heating of foods to serving temperature, including in the military field or in long-duration space missions. Additionally to heating, research data strongly suggests that the applied electric field under OH causes electroporation of cell membranes.

Still more research is needed to completely understand all the effects produced by ohmic heating. The effects of the applied electric field, the incident electric current and the applied electric frequency during ohmic heating over different microorganisms and foods (at molecular and cellular level) still need to be more deeply studied. If confirmed, the electroporation effect or any other temporary permeabilization effect on cellular membranes that occurs during ohmic heating may have significant economic consequences to industry (Sastry, 2008). Therefore understanding, characterizing and modeling this phenomenon is required in order to optimize and possibly exploit its effects.

Also more research is required addressing cold-spots identification and measurement during complex foods processing (*e.g.* multiphase foods). Scientific data (Orangi, Sastry, & Li, 1998; Salengke, 2000; Sastry, 1992; Zhang & Fryer, 1993) presents a variety of scenarios wherein cold-spots occur but still more development in this area is required (Sastry, 2008). Studies on modeling, prediction and determination of the heating pattern of complex foods are also required to assist on the design of food sterilization or pasteurization processes and for the successful development of a final product package that enables the application of ohmic heating.

Acknowledgment

The authors thank the financial support from CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brazil), CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil) and FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo, Brazil).

References

An, H. J., & King, J. M. (2007). Thermal characteristics of ohmically heated rice starch and rice flours. *Journal of Food Science*, *72*(1), C84–C88.

Biss, C. H., Coombes, S. A., & Skudder, P. J. (1989). The development and application of ohmic heating for the continuous heating of particulate foodstuffs. In J. A. Field, & J. A. Howell (Eds.), *Process engineering in the food industry* (pp. 11–20). London UK: Elsevier.

Castro, I. (2007). *Ohmic heating as an alternative to conventional thermal treatment*. PhD. Dissertation, Portugal: Universidade do Minho.

Castro, I., Teixeira, J. A., Salengke, S., Sastry, S. K., & Vicente, A. A. (2004). Ohmic heating of strawberry products: electrical conductivity measurements and ascorbic acid degradation kinetics. *Innovative Food Science and Emerging Technologies*, *5*, 27–36.

Castro, I., Teixeira, J. A., & Vicente, A. A. (2003). The influence of field strength, sugar and solid content on electrical conductivity of strawberry products. *Journal of Food Process Engineering*, *26*, 17–29.

Cho, H. Y., Yousef, A. E., & Sastry, S. K. (1996). Growth kinetics of *Lactobacillus acidophilus* under ohmic heating. *Biotechnology and Bioengineer*, *49*(3), 334–340.

Cho, H. Y., Yousef, A. E., & Sastry, S. K. (1999). Kinetics of inactivation of *Bacillus subtilis* spores by continuous or intermittent ohmic and conventional heating. *Biotechnology and Bioengineer*, *62*(3), 368–372.

Coster, H. G., & Zimmermann, U. (1975). The mechanism of electric breakdown in membranes of *Valonia utricularis*. *Journal of Membrane Biology*, *22*, 73–90.

De Alwis, A. A. P., Halden, K., & Fryer, P. J. (1989). Shape and conductivity effects in the ohmic heating of foods. *Chemical Engineering Research and Design*, *67*, 159–168.

Fryer, P., & Zhang, L. (1993). Electrical resistance heating of foods. *Trends in Food Science and Technology*, *4*(11), 364–369.

Halden, K., De Awis, A. A. P., & Fryer, P. J. (1990). Changes in the electrical conductivity of foods during ohmic heating. *Internatinal Journal of Food Science and Technology*, *25*, 9–25.

Imai, T., Uemura, K., Ishida, N., Yoshizaki, S., & Noguchi, A. (1995). Ohmic heating of Japanese White Radish *Raphanus sativus* L. *International Journal of Food Science and Technology*, *30*, 461–472.

Kim, H. J., Choi, Y. M., Yang, T. C. S., Taub, I. A., Tempest, P., Skudder, P., et al. (1996). Validation of OH for quality enhancement of food products. *Food Technology*, *50*, 253–261.

Kulshrestha, S., & Sastry, S. K. (2003). Frequency and voltage effects on enhanced diffusion during moderate electric field (MEF) treatment. *Innovative Food Science and Emerging Technologies*, *4*(2), 189–194.

Lebovka, N. I., Praporscic, I., Ghnimi, S., & Vorobiev, E. (2005). Does electroporation occur during the ohmic heating of food? *Journal of Food Science*, *70*(5), E308–E311.

Lima, M., Heskitt, B. F., Burianek, L. L., Nokes, S. E., & Sastry, S. K. (1999). Ascorbic acid degradation kinetics during conventional and ohmic heating. *Journal of Food Preservation*, *23*, 421–434.

Lima, M., & Sastry, S. K. (1999). The effects of ohmic heating frequency on hot-air drying rate and juice yield. *Journal of Food Engineering*, *41*, 115–119.

Loghavi, L., Sastry, S. K., & Yousef, A. E. (2008). Effect of moderate electric field frequency on growth kinetics and metabolic activity of *Lactobacillus acidophilus*. *Biotechnology Progress*, *24*, 148–153.

Loghavi, L., Sastry, S. K., & Yousef, A. E. (2009). Effects of moderate electric field frequency and growth stage on the cell membrane permeability of *Lactobacillus acidophilus*. *Biotechnology Progress*, *25*(1), 85–94.

Orangi, S., Sastry, S. K., & Li, Q. (1998). A numerical investigation of electroconductive heating of solid–liquid mixtures. *International Journal of Heat Mass Transfer*, *41*(14), 2211–2220.

Palaniappan, S., & Sastry, S. (2002). Ohmic heating. In V. K. Juneja, & J. N. Sofos (Eds.), *Control of foodborne microorganisms* (pp. 451–460). New York: Marcel Dekker.

Palaniappan, S., & Sastry, S. K. (1991a). Electrical conductivities of selected solid foods during ohmic heating. *Journal of Food Process Engineering*, *14*, 221–236.

Palaniappan, S., & Sastry, S. K. (1991b). Electrical conductivity of selected juices: influences of temperature, solids content, applied voltage, and particle size. *Journal of Food Process Engineering*, *14*, 247–260.

Palaniappan, S., & Sastry, S. K. (1992). Effects of electroconductive heat treatment and electrical pretreatment on thermal death kinetics of selected microorganisms. *Biotechnology and Bioengineering*, *39*, 225–232.

Parrott, D. L. (1992). Use of OH for aseptic processing of food particulates. *Food Technology*, *45*, 68–72.

Pereira, R., Martins, J., Mateus, C., Teixeira, J. A., & Vicente, A. A. (2007). Death kinetics of *Escherichia coli* in goat milk and *Bacillus licheniformis* in cloudberry jam treated by ohmic heating. *Chemical Papers*, *61*(2), 121–126.

Piette, G., Buteau, M. L., De Halleux, D., Chiu, L., Raymond, Y., Ramaswamy, H. S., et al. (2004). Ohmic heating of processed meat and its effects on product quality. *Journal of Food Science*, *69*(2), FEP71–FEP77.

Piette, G., Dostie, M., & Ramaswamy, H. S. (2001a). Is there a future for ohmic cooking in meat processing? *Canadian Meat Science Association News, May 2001*, 8–10.

Piette, G., Dostie, M., & Ramaswamy, H. S. (2001b). Ohmic cooking of processed meats – state of art and prospects. *Procedures of the International Congress of Meat Science and Technology*, *47*, 62–67.

Pongviratchai, P., & Park, J. W. (2007). Electrical conductivity and physical properties of Surimi-Potato starch under ohmic heating. *Journal of Food Science*, *72*(9), E503–E507.

Rice, J. (1995). Ohmic adventures. *Food Processing*, *56*(3), 87–91.

Salengke, S. (2000). *Electrothermal effects of ohmic heating on biomaterials: Temperature monitoring, heating of solid–liquid mixtures, and pretreatment effects on drying rate and oil uptake*. Ph.D. Dissertation. United States of America: The Ohio State University.

Sarang, S., Sastry, S. K., Gaines, J., Yang, T. C. S., & Dunne, P. (2007). Product formulation for ohmic heating: blanching as a pretreatment method to improve uniformity in heating of solid-liquid food mixtures. *Journal of Food Science E: Food Engineering and Physical Properties*, *72*(5), E227–E234.

Sastry, S. K. (1992). A model for heating of liquid-particle mixtures in a continuous flow ohmic heater. *Journal of Food Process Engineering*, *15*(4), 263–278.

Sastry, S. K. (2005). Advances in ohmic heating and moderate electric field (MEF) processing. In G. V. Barbosa-Cánovas, M. S. Tapia, & M. P. Cano (Eds.), *Novel food processing technologies*. Boce Raton, FL: CRC Press.

Sastry, S. K. (2008). Ohmic heating and moderate electric fields processing. *Food Science and Technology International*, *14*, 419.

Sastry, S. K., & Barach, J. T. (2000). Ohmic and inductive heating. *Journal of Food Science Supplement*, *65*(4), 42–46.

Sastry, S. K., Jun, S., Somavat, R., Samaranayake, C., Yousef, A., & Pandit, R. B. (2009). Heating and sterilization technology for long-duration space missions. *Interdisciplinary Transport Phenomena: Annals of NY Academy of Sciences, 1161*, 562–569. doi:10.1111/j.1749-6632.2009.04088.x.

Sastry, S. K., & Palaniappan, S. (1992). Mathematical modeling and experimental studies on ohmic heating of liquid-particle mixtures in a static heater. *Journal of Food Engineering, 15*, 241–261.

Sensoy, I., & Sastry, S. K. (2004). Extraction using moderate electric fields. *Journal of Food Science, 69*, 7–13.

Smith, K. E., Medus, C., Meyer, S. D., Boxrud, D. J., Leano, F., Hedberg, C. W., et al. (2008). Outbreaks of salmonellosis in Minnesota (1998 through 2006) associated with frozen, microwaveable, breaded, stuffed chicken products. *Journal of Food Protection, 71*(10), 2153–2160.

Sun, H. X., Kawamura, S., Himoto, J. I., Itoh, K., Wada, T., & Kimura, T. (2008). Effects of ohmic heating on microbial counts and denaturation of proteins in milk. *Food Science and Technology Research, 14*, 117–123.

Tucker, G. S. (2004). Food waste management and value-added products: using the process to add value to heat-treated products. *Journal of Food Science, 69*(3), CRH102–CRH104.

USA-CDC. United States of America. Department of Health and Human Services. Centers for Disease Control and Prevention. (2008). Multistate outbreak of Salmonella infections associated with frozen pot pies—United States, 2007. *MMWR Morb Mortal Wkly Rep. Nov 28, 57*(47), 1277–1280.

USA-FDA. United States of America, Food and Drug Administration, Center for Food Safety and Applied Nutrition (2000). Kinetics of microbial inactivation for alternative food processing technologies: ohmic and inductive heating. http://www.cfsan.fda.gov/~comm/ift-ohm.html. at: February 17th, 2009.

Vicente, A. A., Castro, I., & Teixeira, J. A. (2006). Innovations in thermal food processes. In Da-Wen Sun (Ed.), *Thermal food processing: New technologies and quality issues* (pp. 424–468). Boca Raton, FL, USA: CRC Press, Taylor & Francis Group.

Wang, C. S., Kuo, S. Z., Kuo-Huang, L. L., & Wu, J. S. B. (2001). Effect of tissue infrastructure on electric conductance of vegetable stems. *Journal of Food Science: Food Engineering and Physical Properties, 66*(2), 284–288.

Wang, W., & Sastry, S. (1993a). Salt diffusion into vegetables tissue as a pretreatment for ohmic heating: electrical conductivity profiles and vacuum infusion studies. *Journal of Food Engineering, 20*, 299–309.

Wang, W., & Sastry, S. (1993b). Salt diffusion into vegetable tissue as a pretreatment for ohmic heating: determination of parameters and mathematical model verification. *Journal of Food Engineering, 20*, 311–323.

Wang, W., & Sastry, S. (1997). Changes in electrical conductivity of selected vegetables during multiple thermal treatments. *Journal of Food Process Engineering, 20*, 449–516.

Yoon, S. W., Lee, C. Y. J., Kim, K. M., & Lee, C. H. (2002). Leakage of cellular material from *Saccharomycies cerevisiae* by ohmic heating. *Journal of Microbiology and Biotechnology, 12*, 183–188.

Zhang, L., & Fryer, P. J. (1993). Models for the electrical heating of solid–liquid food mixtures. *Chemical Engineering Science, 48*, 633–643.