Ohmic Heating Technology in Food Processing – A Review

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Abstract-- **Ohmic heating takes its name from Ohm's law: The food material switched between electrodes has a role of resistance in the circuit. It is a process wherein electric current is passed through materials with primary purpose of heating. To design the ohmic process optimally, the knowledge of electrical conductivity of food materials and mathematical models of ohmic heating patterns is considered important. This paper deals the electrical conductivities of different solid-liquid food materials as affected by temperature, voltage gradients and concentration. The electrical conductivity of food products usually increases with water content and temperature. There is a linear relationship between temperature (T) and electrical conductivity. This paper presents actual and potential applications of ohmic heating, including blanching, pasteurization, sterilization, extraction, enzyme inactivation, fruits and vegetables and waste water treatment.**

***Key Words*:** **Ohmic heating, Electrical conductivity, Mathematical modelling, Applications.**

I. Introduction

Heating is an important step in food processing. Heat treatment has always been the most common method in the food industry for the conservation, cooking and enzymatic inactivation of raw biomaterials. Heat treatment for complex food fluids is considerably improved when newer systems such as microwave heating, inductive or ohmic (or direct electrical) heating are used. These heating methods generate heat inside the food and depend less on thermal conduction and convection and so cause fewer temperature gradients. Inductive heating is restricted to heating metal plates, tubes, screws and coils and the industrial applications are very limited (Goullieux and Pierre, 2005). Ohmic technology is considered a major advance in the continuous processing of particulate food products. Ohmic heating of food products involves the passage of alternating electrical current through them, thus generating internal heat as the result of electrical resistance (Reznick, 1996). This technique was originally developed at the Electricity Research Council, Caphenhurst, United Kingdom and has been recently commercialized by APV Internationals. The basic principle of ohmic heating or joule effect is the dissipation of electrical energy in the form of heat using an electrical conductor. The amount of heat is directly related to the current flow caused by the voltage gradients in the food and the electrical conductivity of the food material (Sastry and Li, 1996).

Electrical conductivity is the main parameter in ohmic heating. Biological materials are one of the largest classes of poor heat conductors. The heating effect depends on the moisture content and concentration of ions in it. For most food stuffs, the electrical conductivity varies mainly depending on the temperature and voltage gradients used. For purely liquid foods, the electrical conductivity increases linearly with temperature but overall falls as the concentration of pulp in it increases (Palaniappan and Sastry, 1991). In solid foods, the situation is more complicated as the electrical conductivity rises linearly with temperature, especially at low voltage gradients and may be different in different directions within the solid. The electrical conductivity of foods may be manipulated by altering its ionic concentration (Lewis and Heppell, 2000). This technology provides rapid and uniform heating. The absence of a hot surface in ohmic heating reduces fouling problems and thermal damage to a product (Sastry and Barach, 2000). Food, which contains water and ionic salts in abundance is the most suitable for ohmic heating (Palaniappan and Sastry, 1991).

The future utilization of ohmic heating by the industry will depend on development of adequate safety and quality assurance protocols. One crucial component in understanding the process lies in the development of mathematical models, which can then be used to simulate various effects of critical factors. Two different modelling approaches currently have been published, De Alwis – Fryer model and Sastry – Palaniappan model. De Alwis and Fryer (1990) use the solution to Laplace's equation to calculate heat generation rate together with the transient energy balance equations to model a single particulate immersed in a fluid medium without convection. This model has been extended by Zhang and Fryer (1993) to include multiple spheres uniformly distributed on a lattice within a non-convective fluid. Sastry and Palaniappan (1992) used circuit analogy to approximate electrical conductivity and thus the heat generation for a static heater with a particle immersed in a well – mixed fluid (assuming infinite convective heat transfer within the fluid). Sastry extended this approach to a continuous flow ohmic heater for high solid concentration. The effective electrical resistance can be determined using the circuit analogy. The effects of convection were over simplified in the two models. In reality: the convection heat transfer rate is neither zero nor infinity. A more general model is thus required and convection effects must be included to model the temperature profile (Ruan et *al*, 2001).

Ohmic heating 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 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).

II. Electrical conductivity – the critical parameter

A laboratory scale OH was used to determine the electrical conductivity of apricot and peach purees. The diameter of the electrodes was 2.5 cm and distance between the electrodes was kept 3 cm. Voltage gradients were applied in the range of 20-70 V/cm. The electrical conductivity of peach and apricot puree was observed to be in the range of 0.53-0.85 and 0.65-1.28 S /cm in the temperature range of 25-60˚C. The temperature beyond 60˚C posed problem due to excessive bubbling. Thus, the rate of change of temperature for the apricot puree was higher than peach puree at all voltage gradients applied. (Icier and Ilicali, 2005)

Electrical conductivity of six different fresh fruits (red apple, golden apple, peach, pear, pineapple and strawberry) and several different cuts of three types of meats (chicken, pork and beef) were increased linearly with the temperature range of 25-140˚C. The linear model equation by Palaniappan and Sastry was used to fit the electrical conductivity data of fruit and meat samples with high coefficient of determination (R^2 >0.97) (Sarang *et al* ,2008)

Apart from temperature and voltage gradient, the other factors which influence electrical conductivity are porosity, hardness, bulk density etc. The electrical conductivity increases due to heating of biological tissue. This may be due to increase in the ionic mobility because of structural changes in the tissue like cell wall protopectin breakdown, expulsion of non-conductive gas bubbles, softening and lowering in aqueous phase viscosity, etc.

The orange juice concentrates having 0.20-0.60 mass fraction were ohmically heated by using five different voltage gradients (20-60 V /cm). The electrical conductivity values were in the range of 0.15-1.25 S /cm showing an increasing trend with decreasing concentration. (Icier and Ilicali, 2005)

Yongsawatdigul *et al* (1995) measured the electrical conductivity of pacific whiting surimi paste using OH with various moisture contents (75,78,81and 84%) and added salt (1,2,3 and 4%) with the alternating current of 3.3,6.7 and 13.3 V /cm. Electrical conductivity of surimi increased with increase in temperature and salt content. Electrical conductivity correlated linearly with temperature ($r^2 \approx 0.99$) and the effect of applied voltage was insignificant. Thus, the electrical conductivity was observed to be strongly dependent on concentration and temperature rather than voltage gradients.

III. Effect of Ohmic Heating on quality of Food products

Conventional heating methods used in the food industry rely on conductive, convective or radiative mechanisms from the heating medium (air, water. oil etc) to the food product. Depending on the product geometry, it may take considerable time to conduct sufficient heat into the product core to reach a safe end-point temperature. This may cause some parts of the product to be overcooked, or undercooked, and adversely affect the quality.

The ground beef samples having different initial fat contents (2, 9 and 15%) were cooked ohmically (20, 30 and 40 V /cm) and conventionally. Ohmically cooked samples were firmer than those conventionally cooked but yield and fat retention was similar. However, the reduction in volume during cooking was significantly smaller from 5.36 to 6.97 % in ohmic cooking than the conventional system which was measured from 26.01 to 31.59 %. Thus, the ohmic cooking was observed to be faster than the conventional cooking ($p < 0.05$). The voltage gradient applied during ohmic cooking was not related to the quality of cooked meat. (Bozkurt and Icier, 2010)

Icier and Ilicali (2005) investigated the use of tylose as a food analog in ohmic heating studies. In this study, it was observed that as the temperature increased the electrical conductivity of the minced beef samples increased upto a critical temperature of 45-50 and then the rate has decreased. The lower critical temperature values were obtained at the high-voltage gradients for the minced beef samples. However, for the tylose samples, the electrical conductivity values increased as the temperature increased upto 60℃. The decrease in electrical conductivity could be due to chemical reactions induced by the effect of increase in temperature and the electrical current. Denaturation of proteins and gelatinization of starch have been observed to cause reduction in electrical conductivity (Wang and Sastry 1997).

It was observed that the tylose samples having 0.5 % and 0.67 % salt contents gave similar ohmic heating rates and the electrical conductivity variations with the minced beef samples having higher and lower fat contents, respectively.

Bozkurt and Icier (2009) evaluated the effects of ohmic heating on the rheological characteristics of quince nectars and compared them with the results of conventional heating. The rheological constants of quince nectar were determined for different holding times (0,10,15,20 and 30 minutes) in the temperature range of 65-75 ℃ by using concentric type viscometer. Shear stress- shear rate data were fitted to the Newtonian, Bingham, Herschel Bulkley, Power law and Casson models. The Herschel-Bulkley model best fitted the experimental data for all temperatures. The activation energy values of 9.88 ± 3.24 kJ/mol and 10.08 ± 2.53 kJ/mol for ohmic heating and conventional heating were obtained respectively. Therefore, ohmic heating could be recommended as an alternative fast heating method for fruit nectars.

Ohmically heating fruit and vegetable tissue has been shown to increase hot-air drying rate, shift desorption isotherms, and increase juice extraction yields with respect to untreated, conventionally heated and microwaved samples. Sweet potato cubes were ohmically heated to three endpoint temperatures using three electrical field strengths and were then placed in a freeze dryer. Moisture content vs. time data were collected and modelled. Results showed that the vaccum drying rates of ohmically heated samples were faster than raw samples for most treatment combinations, and that the maximum reduction of drying time was 24 %. Minimal ohmic treatment can result in a significant decrease in vaccum drying time, which could have important economic and product quality implications (Zhong and Lima, 2003)

Lima and Sastry (1999) studied the effect of ohmic heating frequency on hot air drying rate of yam and juice yield of apples. In this study, hot-air drying rate of yam and the juice yields of apples were compared using a 60 Hz sine wave and a 4 Hz sawtooth wave to determine if lowering the frequency would result in additional improvements to these processes. The 4 Hz sawtooth wave resulted in a faster hot-air drying rate of yam cylinders than the 60 Hz sine wave. The drying rates of the 4 Hz pre-treated samples were significantly greater during most of the drying process, with the most pronounced differences occurring during intermediate stages of drying. The electric field strength affected the drying curves in the range tested at 4 and 60 Hz. Apple juice yield was improved by ohmic pre-treatment, with 4 Hz sawtooth samples yielding significantly greater quantities than the 60 Hz sinusoidal pre-treatment. Due to increased electrical conductivity at 4 Hz, pre-treatment at this frequency require considerably less time than pre-treatment's at 60 Hz. The efficiency of mass transfer processes appears to be significantly dependent on waveform and frequency of alternating current

IV. Mathematical Modelling of an Ohmic Heating System

Mathematical modelling has been used as an invaluable aid in the development, understanding and validation of emerging thermal technologies like ohmic heating. The mathematical model of the thermal process should be able to identify possible hot and cold spots quantify heat losses and evaluate the influence of key variables such as electrical field strength and sample conductivity (Tijskens *et al* 2001)

Bozkurt and Icier (2010) evaluated the performance of ohmic cooking process by applying exergy analysis. It is a measure of availability of energy in the system by reducing irreversibilities in a cooking system. The cylindrical shaped ground beef samples having a diameter of 0.025m and length of 0.05m having initial fat levels of 2 , 9 and 15 % were heated ohmically in a unpressurized batch type ohmic heating system by applying voltage gradients of 20,30 and 40 V /cm by using frequency at 50 Hz. The minimum and maximum exergy efficiency values were obtained to be 63.2 and 89.2 % for initial fat content of 15 % at 40 V /cm and initial fat content of 2 % at 20 V /cm voltage gradient respectively. It was concluded that exergy analysis gave more reliable evaluation about the performance of thermal processing of food products.

Marra *et al* (2009) developed a mathematical model of mashed potato which was heated in a cylindrical batch ohmic heating cell imposing a voltage of 100 V. The heat transfer occurring during ohmic processing of a solid-like food stuff was described by the classical unsteady state heat equation given by Jun and Sastry 2007.

No cold spots within the products were detected but both experimental and model data analysis showed cold regions and heat losses to the electrode and cell surfaces. Therefore, the designed model could be used to optimize and validate safe pasteurization processes for other solid food materials.

Roux *et al* (2010) designed ohmic reactor to study the kinetics of thermal reactions in liquid products like milk. Two liquid dairy products were treated in a laboratory scale static batch ohmic reactor. The three phases of the temperature kinetics- heating, holding and cooling could be modelled using semi-empirical equations based on the joule effect and conductive heat losses. Although the heating and holding models could certainly be refined their predictive performances were relatively satisfactory. The hypotheses determined for the reactor (temperature uniformity and constant volume) and the product (constant density and specific heat capacity) appeared to be appropriate. The semi-empirical model developed for cooling did not perform as well as that designed for heating and holding models. Reproducible thermal profiles were obtained with a 2.3 % relative variation for the heating phase, 1 % for holding and 20 % for cooling. The ohmic reactor enabled determination of the electrical conductivity of the product under the real thermal conditions with a precision of $\pm$ 15 %. These models could therefore be used to predict instantaneous temperature conditions and in a kinetic model of thermal reactions. This approach should make it possible to combine heat transfer and chemical reaction during real food processing.

Modelling of ohmic heating patterns of solid-liquid food complex that contain three different solid particles (carrot, potato and meat) with substantially different electrical conductivities and 3 % Nacl solution were simulated using computational fluid dynamics (CFD) codes with user defined functions (UFDs) studied by Shim *et al* (2010). The predicted temperature values showed maximum prediction error of 6 ℃. Hot spots existed on the continuous phase in the zone perpendicular to the solid cubes and cold spots were in between the particles where the current density lacks. CFD model successfully predicted thermal profiles for multiphase food mixtures while designing an ohmic heater system ensuring uniform heating, food safety and quality.

V. Applications

A large number of actual and potential applications exist for ohmic heating including blanching, evaporation, dehydration, fermentation, extraction, sterilization, pasteurization, heating of foods and waste water treatment. Some of these applications are discussed as below:

A. *Extraction*

The application of ohmic heating in conjunction with extraction processes increased the extraction efficiency of sucrose from sugar beets (Katrokha *et al*1984). Diffusion of beet dye from beetroot into a carrier fluid was increased in ohmic heating and the amount of dye extracted was proportional to the electrical field strength used (Lima *et al* 2001). Ohmic heating improved the extraction of soymilk from soybeans (Kim and Pyun 1995)

Lakkakula *et al* (2004) studied the rice bran stabilization and rice bran oil extraction using ohmic heating. The experiment was carried by adjusting the raw rice bran moisture content to 21 %. Free fatty acid concentration increased more slowly than the control for raw bran samples subjected to ohmic heating with no corresponding temperature rise, indicating that electricity has a non-thermal effect on lipase activity. Ohmic heating increased the total percent of lipids extracted from rice bran to a maximum of 92 %, while 53 % of total lipids were extracted from the control samples. Lowering the frequency of alternating current significantly increased the amount of oil extracted, probably due to electroporation. Results showed that ohmic heating is an effective method for rice bran stabilization with moisture addition.

B. Enzyme Inactivation

Several enzymes are used in food industry for improving food quality (for example, texture and flavour), for the recovery of by-products and for achieving higher rates of extraction. On the other hand, enzymes may also have negative effects on food quality such as production of off-odors and tastes and altering textural properties. Therefore, control of enzymatic activity is required in many food processing steps to promote/inhibit enzymatic activity during processing. Studies on the degradation kinetics of various enzymes were conducted by several authors to determine the effects of pulse electric fields on enzymes inactivation (Barbosa-Canovas and others, 1998; Castro and others, 2001; Ho and others, 1997; Grahl and Markl, 1996)

Castro *et al* (2004) studied the effect of electric field on important food processing enzymes. The tested enzymes were polyphenoloxidase (PPO), lipoxygenase, pectinase, alkaline phosphatase and β-galactosidase, and the inactivation assays were performed under conventional and ohmic heating conditions. The thermal history of the samples (conventional and ohmically processed) was made equal to determine if there was an additional inactivation caused by the presence of an electric field, thus eliminating temperature as a variable. All the enzymes followed 1st-order inactivation kinetics for both conventional and ohmic heating treatments. The presence of an electric field does not cause an enhanced inactivation to alkaline phosphatase, pectinase, and β-galactosidase. However, lipoxygenase and polyphenoloxidase kinetics were significantly affected by the electric field, reducing the time needed for inactivation.

Fresh grape juice was ohmically heated at different voltage gradients (20, 30 and 40 V /cm) from 20˚C to temperatures 60, 70, 80 or 90˚C and the change in the activity of polyphenoloxidase enzyme (PPO) was measured. The critical deactivation temperatures were found to be 60˚C or lower for 40 V /cm, and 70 for 20 and 30 V /cm. various kinetic models for the deactivation of PPO by ohmic heating at 30 V /cm were fitted to the experimental data. The simplest kinetic model involving one step first-order deactivation was better than more complex models. The activation energy of the PPO deactivation for the temperature range of 70-90˚C was found to be 83.5 kJ/mol. (Icier *et al*, 2008)

C. Blanching

Icier *et al* (2006) studied the peroxidise inactivation and colour changes during ohmic blanching of pea puree. The ohmic blanching was performed by application of four different voltage gradients in the range of 20-50 V /cm, the puree samples were heated from 30 to 100 °C to achieve adequate blanching. The conventional blanching was performed at 100 water bath. The ohmic blanching applied by using 30 V /cm and above voltage gradient inactivated peroxidase enzyme at less time than the water blanching. The ohmic blanching at 50 V /cm gave the shortest critical inactivation time of 54s with the best colour quality. First order reaction kinetics adequately described the changes in colour values during ohmic blanching. Hue angle is the most appropriate combination (R^2 =0.954), which describes closely the reaction kinetics of total colour changes of pea puree for ohmic blanching at 20 V /cm.

D. Waste water treatment

Waste water treatment is one of the problems in surimi production due to high volume and high biological oxygen demand (BOD) of water. Protein coagulation by heating and subsequent separation is the method to reduce the BOD of waste water having high protein concentration. Ohmic heating is an efficient heating method that uses electric energy to directly heat the fluid. Thus ohmic heating might be a viable alternative for waste water treatment in surimi production plants (Sastry 1994, Huang *et al* 1997).

Kanjanapongkul *et al* (2009) developed a continuous ohmic heating system to coagulate protein from surimi waste water to reduce the biological oxygen demand of the waste water. A simple model, based on the energy conservation equation, was used to predict the temperature profiles of the waste water. Samples were diluted and Nacl solution (10 % by wt.) was added to make them suitable for testing in the developed device. All samples were heated under different conditions (electric field strength of 20, 25 and 30 V /cm; flow rates of 100, 200 and 300 cc/min). After heating the samples were centrifuged and the remaining protein in supernatants was measured and compared with the results from the previous batch experiments. Heating under higher electric field strength and lower flow rates values resulted in higher temperatures of samples. The predicted temperature values agreed well with the experimental results. The amount of the remaining protein was also in agreement with that of the previous work. The lab-scale ohmic heating system possessed good performance to coagulate protein (~60 %) from surimi waste water.

E. Starch gelatinization

Gelatinization temperature is one of the most important parameters during gelatinization of starch. Wang and Sastry 1997 proposed that the determination of starch gelatinization by ohmic heating is effective as compared to other methods. Fa-De Li *et al* (2004) measured starch gelatinization temperature by changing electrical conductivity of native starch suspensions which was ohmically heated with agitation to 90 °C using 100 V AC at 50 Hz. During gelatinization electrical conductivity of starch suspensions decreased due to migration of charged particles. Further, the gelatinization temperature was determined from d /dT-T curve used with DSC thermogram.

F. Sterilization

Jun *et al* (2007) developed a reusable pouch with electrodes for long term space missions. The pouch permits reheating and sterilization of its internal contents. The 3D model designed ensures sterility and permits identification of cold spots over the entire pouch. This 3D model was observed to be useful tool to optimize electrode configurations and to assure adequate sterilization process.

G. Milk fouling

Stancl and Zitny (2010) studied milk fouling by using the technology of direct ohmic heating. This work evaluates influence of material (stainless steel. TiN, and graphite electrodes), flow rate, electric current density (at constant frequency 50 Hz) and temperature (in a limited temperature range 65-75°C), upon the fouling of skimmed milk during direct ohmic heating. Results proved that the stainless steel electrodes are the worst while the graphite electrodes, where no fouling was observed, are the best, thus confirming the significant role of corrosion and electrical phenomena.

Ayadi *et al* (2005) studied the hydrodynamic behaviour of milk in a flat ohmic cell. Fouling of fluid occurs due to quantity deposit is greater in the zone where the temperature is lowest (entrance zone) and velocity is non-uniform. During continuous ohmic heating there is a chance of slightest hydrodynamic disturbance which results in a thermal and electric disturbance and there by creates zones, which subject to fouling.

VI. CONCLUSION

Ohmic heating is an emerging technology; it provides a large number of industrial applications. The main principle of ohmic heating or joule effect is the dissipation of electrical energy in the form of heat using an electrical conductor. The amount of heat directly related to the current flow caused by the voltage gradients in the food and the electrical conductivity of food materials. The knowledge of electrical conductivity of food materials and mathematical models are considered important for the designing of ohmic heating system. The predictions of mathematical model using electrical conductivity equations were found to be very accurate. More research is required to maintain the uniform heat generation rate which may be easily affected by the electrical heterogeneity of the particle, heat channelling, complex coupling between temperature and electrical field distributions and particle shape and orientation. There is also a need for the development of ohmic heating system for large scale food processing applications and also research is needed for the development of ohmic heating system for domestic purposes.

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