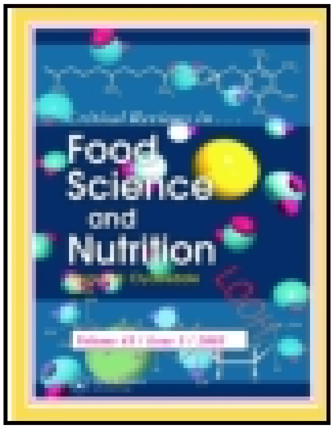

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Ohmic Heating: Concept and Applications- A Review

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ABSTRACT

Ohmic heating, also known as Joule heating, electrical resistance heating, direct electrical resistance heating, is a process of heating the food by passing electric current. In ohmic heating the energy is dissipated directly into the foods. Electrical conductivity is a key parameter in the design of an effective ohmic heater. A large number of potential applications exist for ohmic heating, including blanching, evaporation, dehydration, fermentation, sterilization, pasteurization and heating of foods. Beyond heating, applied electric ýeld under ohmic heating causes electroporation of cell membranes which increases extraction rates, reduced gelatinization temperature and enthalpy. Ohmic heating results in faster heating of food along with maintenance of colour and nutritional value of food. Water absorption index, water solubility index, thermal properties and pasting properties are altered with the application of ohmic heating. Ohmic heating results in pre-gelatinized starches which reduces the energy requirement during processing. But its higher initial cost, lack of its applications in foods containing fats and oils and less awareness limits its use.

Keywords: Ohmic heating, electrical conductivity, electroporation, electric field, food

INTRODUCTION

Heating is one of the oldest means of processing and preservation of foods and has been used by mankind for past many years. Heating technologies have observed marvelous advancements with the development of technologies such as ohmic heating, dielectric heating (which includes microwave heating and radio frequency heating) and inductive heating. All the advanced methods of processing are highly energetic and efficient as the heat is generated directly inside the food. These are called novel thermal processing technologies.

Ohmic heating, also called Joule heating, electrical resistance heating, direct electrical resistance heating, electroheating or electroconductive heating, is defined as a process where heat is internally generated due to electrical resistance, when electric current is passed through it (Alwis and Fryer, 1990). Ohmic heating is distinguished from other electrical heating methods as the electrodes are contacting the foods unlike in microwave and inductive heating where electrodes are absent, the frequency applied is less as compared to radio or microwave frequency range and also the waveform is unrestricted, although typically sinusoidal. A successful application of electricity in food processing was developed in the 19th century to pasteurize milk called ñElectropure Processò (Getchel, 1935). But this application was discouraged apparently due to high processing costs (Fryer and Li, 1993). Also, other applications were abandoned because of the short supply of inert materials needed for the electrodes (Mizrahi et al.,1975). However recently research has been carried out by various scientists worldwide in fruits, vegetables and meat products , flours and starches etc (Palaniappan and Sastry, 1991; Palaniappan and Sastry, 1991; Wang, Sastry, 1997, Castro et al.,2003 and An and King, 2007).

The ohmic heating system helps in the production of highly shelf-stable products with proper maintenance of the colour and nutritional value of food.

FACTORS AFFECTING OHMIC HEATING

Many factors like electrical conductivity, field strength , particle size, concentration, ionic concentration and electrodes have been found to influence the values of ohmic heating rate of a food. The most important parameter in ohmic heating modeling is electrical conductivity (Fryer and Li, 1993).When more than one phase is present, these parameters can exert their influence *via* the effective conductivity of the mixture (ů*eff*) which is the case of particle size and concentration, or they can directly influence the heating rate of the different constituents, which is the case of particle orientation and geometry. Particle geometry was demonstrated to be of importance only when the aspect ratio of the solid particle is far from unity (Larkin and Spinak, 1996). If aspect ratio of the solid particle is not unity, then for a static ohmic heating system containing a fluid and a single elongated particle with a lower conductivity than the fluid, de Alwis *et al.* (1989) showed that when the particle was placed with its axis parallel to the electric field, then it would heat slower than the fluid. However, if such a particle would be placed with its longer axis perpendicular to the electric field then the particle would heat faster than the fluid. Since there is very limited experience in ohmic heating on industrial scale, all the parameters that could be involved must be considered in the process design

Electrical conductivity

The design of effective ohmic heaters depends on the electrical conductivity of foods (Sarang *et al,* 2008). The rate of ohmic heating is directly proportional to the square of the electric ýeld strength and the electrical conductivity (Sastry and Palaniappan, 1992). Most of the experiments have been conducted on the electrical conductivity of liquid fruit products like juices and purees (Palaniappan and Sastry, 1991; Icer and Ilicali, 2005; Castro et al., 2004). Mitchell and de Alwis (1989) evaluated electrical conductivity of pear and apple at 25°C. Electrical conductivity of fresh strawberry over 25ï 100° C temperature range was measured by Castro et al. (2003). Electrical properties of meat have also been investigated in recent years (Saif et al., 2004). Conductivities of chicken (Mitchell and de Alwis, 1989; Palaniappan and Sastry, 1991) beef (Kim et al., 1996) and pork (Halden et al., 1990) were investigated without considering the size of the cut. Tulsiyan et al. (2008) measured conductivity of chicken breast over the sterilization temperature range. Shirsat et al. (2004) reported conductivities of different pork cuts at 20°C and observed that lean is highly conductive compared to fat. Darvishi *et al.*, 2013 observed that electrical conductivities decreased with temperature rise after the commencement of bubbling. The decrease in electrical conductivity may be caused by increased concentration of solids (due to evaporation of water) causing a drag in the ionic movement

Field Strength

Greater the electric field intensity, higher is the electrical conductivity and faster is the heating rate. The effects of field strength and multiple thermal treatments on electrical conductivity of strawberry products were investigated by Castro et al., 2004. An increase of electrical conductivity with field strength was observed for two strawberry pulps and strawberry filling but not for strawberry topping or strawberry-apple sauce. The heating process causes

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membrane destruction and consequently the free water content increases (Bean et al., 1960; Halden, De Alwis and Fryer, 1990; Sasson and Monselise, 1977). The field strength application results in increasing fluid motion through the capillaries, which is directly proportional to electrical conductivity (Halden et al., 1990). Higher strength ýelds (104ï 105 V/cm) resulted in effective inactivation of microbes (Barbosa-Canovas et al., 1998). Extraction and expressing processes were enhanced in different food materials with electric field strength under 100 V/cm (Wang and Sastry, 2002; Kulshrestha and Sastry, 2003; Zhong and Lima, 2003 and Praporscic et al., 2006. Icier and Ilicali (2005) also postulated that at higher voltage gradients, the current passing through the sample was higher and this increased the heat generation rate within the sample. Similar trends were reported by Icier et al. (2006) while studing the peroxide inactivation and colour changes during ohmic blancing of pea puree. An and King (2007) and Icier et al. (2008)also reported that with the increase in voltage, electrical conductivity and thus heating rate was also enchanced.

Particle Size

The rate of heating in ohmic heating is affected by particle size (Kim et al., 1996). Zareifard et al. (2003) observed that heating rate decreased with the increase in particle size of carrot. They observed that the heating time to achieve the same temperature rise increased with particle size. Similar results were reported by Palaniappan and Sastry (1991a) who concluded that electrical conductivity decreased as the particle size increased. Thus the rate of heating decreased as the particle size increased. Benabderrahmane and Pain (2000) observed the similar results, demonstrating less liquid heating efficiency as particle diameter increased.

Particle Concentration

Sastry (1991) found that particle concentration is a decisive factor in determining the heating rate of the two phases. Castro *et al.*(2003) observed the reduction in electrical conductivity of strawberry pulp as the strawberry concentration in the pulp increased. The pulp P1 (initial pH value of 4.0, Brix value of 14.5° and 2.5% (wyw) of starch content) has greater value of electrical conductivity than the pulp P2 (pH value of 4.0, Brix value of 26.5° and no starch). Zareifard et al., (2003) came to the conclusion that much longer heating time (twice as much) was required to raise the temperature from 20°C to 80°C than when the solid concentration was less as the bulk density decreased with the increase in particle size. They also postulated that heating time increased with concentration of carrot cubes within the food system and results are in agreement with previous findings of Sastry and Palaniappan (1992), as well as Benabderrahmane and Pain (2000). The effect of concentration on the ohmic heating rates of apple and sour-cherry juices was evaluated by Icier and Ilicali (2004).The rate of ohmic heating was reported to be improved with the decrease in the concentration of the juices from 60% to 20%. Since the solid contents of the purees used in this study were lower than those of the fruit juices used in the above reference, the ohmic heating rates of the fruit purees were obtained as higher than the concentrated fruit juices at all voltage gradients (20-70 V/cm)

Ionic Concentration

Increase in the electrical conductivity during heating of biological tissue occurs 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 (Bean et al., 1960; Sasson and Monselise, 1977). Greater the ionic concentration faster is the heating rate. Icier and Ilicali, 2005 concluded that apricot puree, being more acidic, was heated at faster rate than peach puree. Sarang et al., 2008 evaluated the effect of ionic concentration on ohmic heating of fruits and meat and reported that higher ionic concentration have a considerable effect on the heating behaviour of processed material using the ohmic heating technique. De Alwis et al. (1989) studied the effect of electrical conductivity of strawberry and peach and concluded that greater electrical conductivity may be attributed to the softer tissues and hence higher ionic mobility in comparison to the harder tissues of apples, pineapple and pear. Zell et al., 2009 observed salted meats and minced beef showed the highest electrical conductivity level compared to the intact meat heated in either a parallel or in a perpendicular direction. Shirsat et al. (2004b) suggested that the effect of mincing was to facilitate the release of moisture and inorganic constituents from myofibrillar tissue during the chopping and mincing procedures. Salting also appeared to enhance the conductivity difference caused by fibre orientation. Zell et al., 2009 suggested that injection and tumbling should be carefully done to ensure a uniform salt distribution and thus to optimise the ohmic heating process.

Particle Location

Particle orientation and location also play important role within an ohmic unit system. Davies et al. (1999) demonstrated the effect of particle orientation with respect to one another. The ohmic heating behaviour of a mass of particles as influenced by their location with respect to electrodes was investigated by Zareifard et al. (2003). The electrode surface was either fully or partially in contact with mass of the particles in ohmic heating cell during heating. It was observed that for the parallel condition, the liquid phase heated faster than the solid phase while in the series condition, the reverse was observed.

Electrodes

Heat losses from the periphery of the food material depends significantly on the type of product containment cell and electrodes, which results in unacceptably high temperature gradients within the product. The electrodes are a potential cause of heat loss during ohmic heating as discussed by De Alwis and Fryer (1990).

Zell et al., 2011reported that the thicker the electrode lower the rate of temperature increase which is a reflection of its larger mass and lower electrical resistance. De Alwis et al. (1989) also found lower temperatures at electrode surface. A large temperature difference was obtained between thermocouples located in the centre of the ohmic heating cell and those located close to the electrodes was observed by Marcotte et al., (1998). Various metals (Stainless steel, titanium, platinised titanium and aluminium) were evaluated by Zell et al. (2011) as electrode material. The study revealed that titanium had higher temperature at electrode surface than stainless steel of same thickness. Thinner aluminium gave highest temperature at electrode interface where as platinised aluminium of similar thickness, the temperature obtained at electrode was minimum. The cooling problem was reported with the thinnest stainless steel electrode while all stainless steel electrodes were prone to electrolysis. Platinised titanium didnœt show any significant electrocatalytic properties towards foods at a frequency of 50 Hz (Tzedakis et al., 1999). Samaranayake et al. (2005) suggested that the risk of product contamination from

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electrode reaction products could be minimised using bipolar pulses of up to 10 kHz, in addition to using platinised titanium electrodes. It was concluded that platinised titanium electrode was verified to be the most suitable as it was resistant to electrolysis, gave a satisfactory heating rate and was suitably robust unlike the thinner aluminium electrodes.

OHMIC HEATING SETUP

Ohmic heating setup mainly consists of a heating cell, electrodes, data logger system, AC power source, voltage control unit and thermocouples. Several scientists used different materials for construction of ohmic heater. Marra et al, 2009 analysed heat transfer during ohmic processing of a solid food. The cell used for the experiments was made of stainless steel, 14.5 cm length, 11.5 cm internal length, 7.2 cm inner diameter and with an outer diameter of 7.6 cm. The inner cell surface was lined with Teflon tape and three thermocouples were inserted at the top of the cell. Thermocouples were prepared with type T thermocouple wires within a stainless steel sheath (2 mm diameter). Platinum coated titanium electrodes (diameter 6.9 cm) were fixed at both ends of the cell and it was spring loaded. It also contains voltage control unit. The control panel was supplied with 230 V, 50 Hz alternating current and an integrated transformer was used to adjust the voltage to 100 V for all runs.

In an experiment conducted on determination of starch gelatinization temperature by ohmic heating, Li et al., 2009 used the set up comprising of a data logger system, T type thermocouple covered with silicon. The voltage applied for ohmic heating was directly measured with the HP data logger. The ohmic heating system included a transformer, flat electrodes made of titanium and a heating box covered with a lid. The power was AC at 50 Hz, and a voltage of 100 V.

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In a study on the ohmic heating of frits and meats , Sarang et al, 2008 used the setup consisting of ten cylindrical ohmic heating chambers equipped with platinized titanium electrodes. Measurements of the electrical conductivity of ten samples was done at temperatures up to 140 C. Samples were clamped at the ends by two electrodes in each cell, and a T-type copper-constantan, Teflon coated thermocouple. The ohmic cells were connected to a relay switch which directed the order in which the cells were heated. Voltage and current transducers were used to measure the voltage across the samples and the current flowing through them. A data logger

was used to record data at constant time intervals.

Icier, 2009 made use of ohmic heating system consisting of a power supply, an transformer (50 Hz), a variable transformer (0ï 240 V) and a microprocessor board during the experiment on influence of ohmic heating on rheological and electrical properties of reconstituted whey solutions. Teflon coated electronic temperature sensors with a compression fitting were used to measure temperatures at the different sections of the sample in the test cell. The microprocessor board (Omega Eng. Inc., Stanford, CT) recorded the temperatures, current and voltage applied and transmitted this information to the microcomputer at constant time intervals (1 s).

Zareifard., 2002 conducted experiment on static Teflon ohmic heating cell unit 2.54 cm thick and an internal radius of 3.5 cm. The distance between electrodes was 20 cm. Two titanium electrodes were connected to the power unit. A constant voltage of 250 V was applied and the maximum current was 10 A. Voltage and current were recorded during heating and used to calculate electrical conductivity. Five type T Teflon coated thermocouples were fixed along the cylinder perpendicularly. Two thermocouples were placed close to each electrode. Two other thermocouples were placed in the way between the centre of the cylinder and the electrode on each side. The last thermocouple was at the centre of the cylinder.

Castro et al, 2004 evaluated ohmic heating of strawberries in system comprising of a cylindrical glass tube of 30 cm total length and 2.3 cm inside diameter. Three thermocouples were used, two at an

equal distance of the centre of the tube and one at the centre. Two Titanium electrodes with Teflon pressure caps were placed at each end of the tube. An alternating current source was also provided to supply frequency of 50 Hz. Temperatures were monitored using type-K thermocouples, placed at the geometrical centre of the chamber. A data-logger was employed to record current intensity, voltage and temperature. Voltage and current transducers were used to measure voltage and current.

APPLICATIONS

Microbial inactivation

Microbial inactivation in relation to ohmic heating is primarily thermal in nature, much like conventional heating. The presence of electric field in ohmic heating may cause mild non thermal cellular damage (Cho et al., 1999; Pereira et al., 2007 and Sun et al., 2008). The low frequency (usually 50-60 Hz) allows cell walls to build up charges and form pores. This is the primary reason for the additional effect of ohmic heating. This effect results in reduced D value required for microbial inactivation as compared to traditional heating methods. This reduction has been observed for Bacillus licheniformis and Escherichia coli (Pietta et al., 2007), Bacillus subtilis (Cho et al., 1999), Streptococcus thermophilus (Sun et al., 2008) and Byssochlamys fulva (Castro, 2007).

Cho *et al.,* (1996) demonstrated that by giving electric pretreatment by ohmic heating, the intensity of additional thermal applications for subsequent microbial inactivation can be reduced. Microbial inactivation curves of ohmic heating are similar to conventional heating curves except for a difference in the slope, which can most likely be explained by the presence of the electric field (FDA-CFSAN, 2000). Ohmic heating is lethal to almost all the micro-organisms, therefore the thermal death kinetic studies available for pathogens and spoilage bacteria may be followed when designing experiments and systems that utilize ohmic heating. 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 and Sastry, 1992).

Pereira et al.,(2007) have concluded lower D and z values for the inactivation of E. coli and B. licheniformis during ohmic heating. In this research, conventional heating was compared against ohmic heating, and the thermal kinetics of the samples analyzed was adjusted to match. The D-values recorded for E. coli at 65°C were 3.5±0.2 and 0.86 min for conventional and ohmic process respectively and the z values were observed to be as 23.1° and 8.4°C respectively. The observed results indicate that the microbial death rate may have been affected by electric current. Similar observations were obtained in the same study for the spore inactivation of B.

licheniformis. Analysing both the microorganisms strain studied in the experiment, ohmic heating presented a lower D value. From the study, it was concluded that due to the presence and effects of the electric current over vegetative cells of E. coli and bacterial spores of B. licheniformis, an additional non-thermal lethal effect occurred under ohmic heating

In the study, executed on the B.subtilis and Bacillus atrophaeus inactivation kinetics by conventional moist heating and ohmic heating, Cho et al., (1999) concluded that the application of an electric ýeld leads to lower thermal inactivation time, for the same temperature of treatment and the D value at T ¼ 92.3°C was reduced by 1 min for ohmic heating when compared to conventional heating by water circulation. Thus possibly it can be infered that the microbial inactivation was affected by the incident electric ýeld 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 bacilli), under identical heating histories. In some cases, however, a mild electrical pretreatment decreased the subsequent inactivation requirements, for E. coli. Minor reduction in the D values was observed by Palaniappan and Sastry (1992), when ohmic heating was applied for the inactivation of Zygosaccharomyces bacilii and E. coli, at temperatures lower than 56°C. But statistically no signiýcant difference between treatments was recorded.

Experiment on the inactivation of milk viable aerobes and S. thermophilus was conducted by Sun *et al.,*(2008). The results demonstrated that ohmic heating causes higher microbial death than the conventional heating process. The ýnal microbial count and the calculated D values for ohmic heating were found to be lower than those acquired from conventional heating, under the same temperature conditions.Therefore, the study reached to the conclusion that ohmic heating caused a thermal lethal effect and an additional non-thermal lethal effect on the studied microorganisms According to Sun et al.,(2008) the inactivation effect of electricity is signiýcant compared to that of heat and was shown to be related to the electrical voltage and frequency whereas under similar time-temperature conditions, for both conventional and ohmic heating little differences between processes could be observed under 50°C when Yoon et al., (2002) investigated the effect of ohmic heating on the structure and permeability of cell membrane of yeast cells (Saccharomyces cerevisiae) but the difference of yeast cell destruction rate under ohmic heating became much prominent at 70-80°C.

An experiment on two stage ohmic heating (ohmic heating, holding period, ohmic heating), using Bacillus subtilis proved that ohmic treatment resulted in accelerated death rates (Cho et al., 1999). Another experiment carried out by (Lee and Yoon, 1999) involving Saccharomyces cerevisae showed that ohmic heating enhanced the leakage of intracellular components as compared with the conventional method of boiling in water. Palaniappan et al. (1992) indicated that electricity did not influence inactivation kinetics but the application of a non-lethal electric field reduces the intensity of the subsequent thermal treatment, which showed that the electric field lowers the heat resistance of microorganisms. Microbial death duringohmic heating was mainly attributed to thermal effects, while insignificant results were observed with the non-thermal effects. Yildiz and Baysal (2006) studied the effects of alternative current heating treatment on Aspergillus niger, pectin methylesterase and pectin content in tomato. It was concluded that the critical treatment time for A. niger decreased as the electric field strength increased. However, the temperature profile was different between the assays. The enhanced inactivation could be due either to higher electric field or simply higher temperature.

Electroporation effect

The cell electroporation is deýned as the formation of pores in cell membranes due to the presence of an electric ýeld and as consequence, the permeability of the membrane is enhanced and material diffusion throughout the membrane is achieved by electro-osmosis (An and King, 2007; Coster and Zimmermann, 1975; Lima and Sastry, 1999). It is assumed that the electric breakdown or electroporation mechanism is dominant for the non-thermal effects of OH (An and King, 2007; Kulshrestha and Sastry, 2003; Sensoy and Sastry, 2004). Electroporation occurs because the cell membrane has a specific dielectric strength, which can be exceeded by the electric field In ohmic heating, the applied electric ýeld causes electroporation of cell membranes. The dielectric strength of a cell membrane is related to the amount of lipids (acting as an insulator) present in the membrane itself. The pores formed can vary in size depending on the strength of the electric field, and can reseal after a short period of time. (Lee and Yoon, 1999) stated that excessive exposure causes cell death due to the leakage of intracellular components through the pores. Therefore, electroporation is highly damaging to a cell and leads to the increased chances of death of the micro-organisms. Another study (Cho et al .,1999), conducted under near-identical temperature conditions, indicates that the kinetics of inactivation of *Bacillus subtilis* spores can be accelerated by an ohmic treatment.

Yoon et al., (2002) observed that under OH the electric ýeld appeared to have both direct and indirect effect on the cell wall, and intracellular materials, containg amino acids, protein, nucleic acids, coenzymes, and related material, were exuded to the culture medium. It was observed that below 50°C, concentration of exuded material in yeast supernatant was similar under both the condition whereas above 50°C, the concentration was higher in ohmic heating as compared to conventional heating. The authors found that the higher exudation rate depends on the destruction rate of the yeast cells and the type of heating method. The inþuence of the electrical ýeld within ohmic heating 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 signiýcantly as the electric ýeld increased from 10 to 20 V/cm. The absorbance at 260 nm typically attributed to nucleic acids was 2-fold ($p < 0.01$) at 20 V/cm and the total protein content was 3-fold higher ($p < 0.01$) when compared with that at 15 V/cm (Yoon et al., 2002).

The application of ohmic heating was studied for the fermentation of Lactobacillus acidophilus by Cho et al., (1996) and Loghavi et al (2008, 2009). In study conducted by Cho et al. (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 with the application of electric ýeld in the process may cause membrane electroporation which results in faster and more efýcient nutrient transport to the interior of the cell, thus reducing the lag phase of the fermentation. However on later fermentative stages productivity decreased as a result of ohmic heating. This may be due to the presence of mild electroporation, which improves the transport of substrates at the early stages of fermentation, thereby accelerating it. At the later stages, the electroporation effect would improve the transport of metabolites into the cell and thereby would inhibit fermentation. (Cho et al., 1996; USA-FDA, 2000). The presence of pore-forming mechanisms on cellular tissue has been authenticated by recent work (Imai et al.,1995; Wang 1995; Kulshrestha and Sastry 1999).

Inactivation of enzymes

Electrical ýelds, applied during ohmic heating caused faster inactivation of lipoxygenase and polyphenoloxidase than during conventional heating (Castro et al., 2004). Similarly, ohmic heating was found to be more efýcient for the required microbial and pectin esterase inactivation due to a shorter residence time when released þavour compounds were not degraded as quickly as during conventional pasteurisation (Leizerson and Shimoni, 2005).

Icier et al.,(2006) investigated peroxidase inactivation and colour changes during ohmic blanching of pea puree. The pea puree samples were blanched by both ohmic and conventional heating methods. The ohmic blanching was carried out at four different voltage gradients in the range of 20ï 50 V/cm. The puree samples were heated from 30°C to 100°C and held at 100°C to achieve appropriate blanching. The conventional blanching was performed at 100°C 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 54 s with the best colour quality. Changes in colour values during ohmic blanching were described by first order reaction kinetics. 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.

Polyphenoloxidase deactivation kinetics during ohmic heating of grape juice was studied by Icier *et al.,*(2008). Fresh grape juice was ohmically heated at different voltage gradients (20, 30, and 40 V/cm) from 20°C to temperatures of 60, 70, 80 or 90°C and the change in the activity

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of polyphenoloxidase enzyme (PPO) was measured. The critical deactivation temperatures were found to be at 60°C or lower for 40 V/cm, and 70°C for 20 and 30 V/cm. Various kinetic models for the deactivation of polyphenoloxidase by ohmic heating at 30 V/cm were ýtted to the experimental data. The simplest kinetic model involving one step ýrst-order deactivation was better than more complex models. The activation energy of the polyphenoloxidase deactivation for the temperature range of 70ï 90°C was found to be 83.5 kJ/mol.

Pectin methylesterase is an enzyme that has been found in essentially every plant tissue, several fungi and bacteria. PME has no prostetic group and catalyses de-esteriýcation of galactosyluronate methylesters of pectins, releasing protons and methanol into the media. The inactivation of exogenous pectin methylesterase in apple juice and cloudberry jams has been found to follow ýrst-order kinetics (Wilinska et al., 2008). Under ohmic heating, the same trend was observed , when experiments for the same materials were carried out.

Ohmic heating using continuous alternating current electric ýeld was applied to orange juice containing Bacillus subtilis spores to examine its inactivation. An effective inactivation of spores was achieved using a pressurised electric sterilization system, using a combination of high temperature and high electric ýeld, in a shorter time. Also the loss in the ascorbic acid and daevelopment of peculiar smell was minimised in ohmic heating (Uemura and Isobe, 2003).

Increased extraction rate

Electric ýelds with ýeld strength under 100V/cm allow enhance extraction and expressing processes in different food materials (Wang and Sastry, 2002; Kulshrestha and Sastry, 2003; Zhong and Lima, 2003). It is necessary to provide ohmic heating at ýeld strength of 100V/cm for treatment time of the order of 1ï 100 s. The electrical breakdown or

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electroporation mechanism was assumed to be dominant in the experiments conducted on extraction and expression processes using ohmic heating (Wang and Sastry, 2002; Kulshrestha and Sastry, 2003; Sensoy and Sastry, 2004).

Praporscic (2006) evaluated the juice yield from potato and apple tissues, as affected by ohmic heating. Two different types of experiments involving different treatment chambers were carried out i.e. textural and conductivity study of cylindrical samples and juice yield tests of tissue slices. The investigations demonstrated that tissue disintegration degree and juice yield depend on the ýeld intensity, temperature, treatment duration and type of plant tissue. The juice extraction was best when the plant tissue was treated electrically at a moderate temperature of 50°C. It was explained by the combined effect of electroporation of cell membranes and thermal softening of tissue. Ohmic heating of apples and potatoes at electric ýeld strength less than 100V/cm allows a high level of membrane destruction and mechanical softening of tissues even at a moderate temperature of 50°C. Juice extraction from pressing was observed to be maximum when the tissue was treated electrically at a temperature of 50°C.

Ohmic heating was used, for example, to increase the efýciency of sucrose extraction from sugar beet (Lima et al., 2001) or to enhance the diffusion of soy milk from soybeans (Kim and Pyun, 1995). Its advantages include maintaining the colour and nutritional value of food, shorter processing times and higher yields during extraction process (Castro et al., 2004; Leizerson and Shimoni, 2005; Vikram et al., 2005; Wang and Sastry, 2002)

In starch and flours

Starches are used in food systems as stabilizing additives, moisture retainers and thickeners. Drum driers and extrusion processes used in the industry for preparing pre-gelatinized starches cause severe degradation of starch granules, increasing the amount of soluble solids. An and King (2007) studied thermal properties of conventionally and ohmically heated rice starch and rice flours at various frequencies and voltages. As the samples were pregelatinized due to ohmic and conventional heating, the gelatinization temperature increased and they became more rigid due to starchï chain interactions. In addition, enthalpy decreased for conventionally and ohmically heated starches during gelatinization. Thus less energy for gelatinization was required during DSC analysis. Ohmically heated commercial starch showed the greatest decrease in enthalpy probably because of the greatest extent of pre-gelatinization through ohmic heating. Brown rice flour showed the greatest gelatinization temperature. Enthalpy of ohmically heated starches at 20 V/cm was the lowest, as the lower voltage resulted in a complete pre-gelatinization from a longer heating time required to reach 100°C. Ohmic treatment at 70V/cm decreased onset gelatinization temperature of white flour, swelling faster swelling rice flour was produced, whereas the conventionally heated sample showed a better thermal resistance.

The effect of starch gelatinization on electrical conductivity was investigated by Wang and Sastry (1997). Suspensions of corn and potato starch were prepared with a starch : water ratio of I:5 (w/w) by mixing with the appropriate amount of water. Suspensions were ohmically heated with agitation to 90°C by AC at 60 HZ and a voltage gradient of 20 V/cm. Partially gelatinized and fully gelatinized samples, prepared by preheating suspensions to or beyond the gelatinization ranges, were also tested. Gelatinization energy and degree of gelatinization (%SG) of each sample were determined by differential scanning calorimetry (DSC) at scanning rate of 10°C /min. The results showed that endothermic gelatinization peaks were found on both DSC thermograms and electrical conductivity curves, with similar shapes and temperature ranges. Data of %SG obtained, from conductivity curves and DSC thermograms were in agreement in low and mid-gelatinization ranges but were different when %SG was high, due to high ohmic heating rate. Electrical conductivity increased with temperature, but decreased with degree of gelatinization, apparently caused by structural changes and an increase in bound water.

Martinez-Bustos et al., (2005) evaluated the use of an ohmic heating process, in which an electric current is passed through the material to generate heat, to minimize loss of solids and to obtain an adequate degree of gelatinization in jicama and cassava starch. Ohmic heating caused greater effects of gelatinization with high voltage and short processing times (123V-10 min). In the case of jicama starch, the water absorption index (50°C) ranged from 3.2 to 4.7% and the water solubility index (50 °C) from 1.2 to 2.2%. For cassava starch, results were 3.7% to 5.4% and 3.2 to 6.1%. From the analysis of viscosity and thermal properties, it was found that 70.0% of the native jicama starch and 39.1% of the cassava starch were gelatinized with maximum voltage and longer processing times. The starches obtained showed different functional properties with diverse degrees of gelatinization that may be used in the food industry.

Li et al., (2004) determined the starch gelatinization by ohmic heating. Suspensions of native starches with different starch/water mass ratios were prepared and ohmically heated with agitation to 90°C using 100 V at 50 Hz and a voltage gradient of 10 V/cm. The results showed that electrical conductivity of native starch suspensions was linear with temperature except for the gelatinization range. It was observed that the shape of dů/dT versus T curve was essentially similar to the endothermic peak on a DSC thermogram, and the gelatinization temperature could be conveniently determined from this curve. The principle reason for the decrease in electrical conductivity of native starch suspensions was probably that during gelatinization, swelling of starch granules reduced the area for motion of the charged particles.

Meats

Several studies of the thermophysical properties of meat products and also their behavior during ohmic heating have been published in recent years. Marcotte et al., (2008) presented data for thermophysical properties of various meat emulsions however, most of these measurements were performed at a limited number of temperatures (20, 40, 60 and 80°C). Electrical conductivity values of different meat cuts during ohmic heating were recorded by Sarang et al.,(2008) using a small scale ohmic heating cell. Shirsat *et al.,*(2004b) reported that addition of lean to fat increased the overall conductivity. In a review by McKenna et al.,(2006) the influence of orientation of larger particles (15-25 mm) on electrical properties and on the relative heating rates of the phases was observed. Significant effect of particle orientation was noticed electrical properties and heating rates. While Brunton et al.,(2006) described the effect of muscle ýbre direction on dielectric properties of beef biceps femoris at room temperature. Ohmic heating has proved successful in heating meat emulsion and meat batters (Shirsat et al., 2004a; Piette *et al.,* 2004). Although some data has been published on dielectric properties of meat ingredients (Lyng et al., 2005) and also a limited amount on electrical conductivity of meats and ingredients (Shirsat et al., 2004c). However more information is required to establish how the electrical conductivity and the heating rate are influenced by the interactions of these ingredients within a meat matrix.

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Zell et al., (2009) compare electrical conductivity values of non-meat ingredients in solution/suspension and when incorporated in a meat product at typical usage levels. The inþuence of fat incorporation was also recorded. Electrical conductivity values of various raw meat products were measured in order to make comparisons. The inþuence of ýbre orientation and salt injection on electrical conductivity of whole beef muscle during ohmic heating process was investigated. Electrical conductivity values of commonly used meat ingredients were recorded when dispersed as 5% (w/w) aqueous solutions/suspensions. Measurements were made from 5 to 85°C and showed a linear increase in electrical conductivity values with increasing temperature. In processed beef, addition of sodium chloride and phosphate caused a signiýcant increase in electrical conductivity which in turn would lead to an increase in ohmic heating rates. Furthermore, whole meats with lower endogenous fat or processed meats with the least added fat displayed higher electrical conductivity and reduced ohmic heating times. Maximum electrical conductivity was examined when ýbres of beef were aligned with the current þow.

Fruits and vegetables products

The nutritional quality of most of the fruits and vegetable products is altered during conventional thermal processing. This necessitates the the search for alternative processing technologies which results in the higher quality end products. The economic viability of ohmic heating technology depends on the possibility of applying it to most of the products processed by this industry (Castro *et al.*, 2003). In the study by Castro *et al.,*(2003), several strawberry based products were tested by ohmic heating. The results proved that for most of the products, high heating rates could be achieved. Also, the increase of the applied electric field could increase the heating rate. The suitability of ohmic heating for strawberry products having different solids concentrations was also evaluated by Castro et al., 2003. Electrical conductivity was observed to be decreased with the increase in solids contents in a mixture of particles, but the decrease was more significant for the bigger particles. The results also suggested that for higher solids content (> 20 % w/w) and sugar contents over 40.0 ºBrix, electrical conductivity is too low to use in the conventional ohmic heaters and a new design is required. Wang and Sastry (1997) studied the effects of an ohmic pre-treatment and found no significant changes in the moisture content of the final products. Conventional blanching treatments may be replaced by ohmic blanching.

It has already been demonstrated that temperature and thermal processing greatly affects the texture of fruits and vegetables (Hoogzand and Doesburg, 1961; Bartolome and Hoff, 1972). The firmness of processed vegetables (e.g. canned cauliflower, asparagus) can be improved by low-temperature, long-time pre-treatments. Eliot et al.,(1999) studied the influence of precooking by ohmic heating on the firmness of cauliflower. The experimental data represented that ohmic heating in combination with low-temperature precooking in saline solutions provides a practical solution to HTST sterilization of cauliflower florets. A similar study was also performed with potato cubes (Eliot et al.,1999; Eliot and Goullieux, 2000), and concluded that an ohmic pre-treatment prevented loss of firmness when compared to a conventional pre-treatment (50 % in some cases).

EFFECT OF OHMIC HEATING ON QUALITY CHARACTERISTICS OF TREATED PRODUCTS

Water Absorption Index (WAI) and WSI (Water Solubility Index)

The WAI and WSI characterize how extruded products will interact with water and are often important in predicting how the ohmically heated samples may behave if further processed. Also, the degree of conversion of starch from granule form during processing can be assessed via WAI and WSI (Sriburi et al., 1999).

Fernando et al, 2000 concluded that ohmically heated starch and flour have more WAI and WSI as compared to untreated starch and flour. This is attributed to modifications that occurred during ohmic heating, permitting these granules more accessibility to water absorption. Also, there are effects of length of amylopectin chains, proportion of long or short chains, and molecular weight of the starch. The starches obtained with ohmic heating had acceptable WAI values and dispersed easily in cold water, with low WSI compared with those obtained by extrusion and drum driers (Colonna et al., 1984; Doublier et al., 1986). Colonna et al. (1987) reports that in pre-gelatinized starches, when no cutting force is applied to the swollen granules, slight partial leaching of amylose occurs, the components of the starch degrade slightly, and probably continue to be connected within a continuous matrix. Thus, these products are highly accessible to water (due to their soft structure) and have only a limited solubility in cold water (due to the components of high molecular weight). They disperse easily in cold water to form moderately stable suspensions and can be used mainly in fruit and potato purées, baby food, dry soup mixes, and as adhesives in the textile industry (Bonazzi et al., 1996).

Pasting properties

Determinations of viscosity are used to measure the degree of fragmentation of the starch granules and the severity of the treatment (Colonna *et al*., 1987). It is likely that ohmic treatment induces changes that reduce the reaccomodation of linear molecules of amylose or segments of amylopectin.

Karapantsios et al.,(2000) studied electrical conductance of starch gelatinization during conventional heating and found that the electrical conductivity had a linear relationship with time until reaching the gelatinization temperature and presented a decreasing trend. Li *et al.,*(2004) found that the electrical conductivity and temperature of a starch suspension had a linear relationship before and after gelatinization. The reason for a decrease in electrical conductivity in the gelatinization range was due to starch granule swelling and viscosity increase, which resulted in a reduction of area for starch particle movement and an increase in the resistance to motion of the swollen particles.

Wang and Sastry, 1997 postulated that gelatinization occurs when starch is heated with excess water. Due to the resultant changes of food physical and chemical properties, gelatinization is one of the most important phenomena in analysis and design of food processes. Determinations of viscosity are used to measure the degree of fragmentation of the starch granules and the severity of the treatment (Colonna et al., 1987). It is likely that ohmic treatment induces changes that reduce the reaccomodation of linear molecules of amylose or segments of amylopectin.

Galvan (2002) reported a higher maximum viscosity for jicama starch than for maize, although lower than cassava and potato starches. Halden et al. (1990) reported that the structural changes during gelatinization of the starch (changes between initial and final viscosity and increments in bonded water during ohmic heating) were due to starch gelatinization provoked by electric conductivity that increases with temperature and decreases with the degree of gelatinization.

Fernando *et al*, 2000 observed that ohmic heating (107-115V and 10-20 mins) exhibited a greater fall in viscosity and total retrogradation (pÒ0.05) of jicama and cassava starch. All of the treatments had lower total retrogradation (Stbk) and reduced final viscosity (VF), relative to native (pÒ0.05). The intensity of starch retrogradation may be due to the fact that under pressure, gelatinization restricts exudation of amylase from the starch granules (Douzals et al., 1998).Voltage was the determining factor (pÒ0.05) for pre-gelatinization.

Thermal Properties

Thermal characteristics of starches are studied using differential scanning calorimetry (DSC). Starch gelatinization is the important factor that determines the overall cooking behavior and product characteristics of foods. During starch heating, there are some changes in properties, enthalpy, specific heat capacity, and gelatinization temperature, showing the extent of starch gelatinization (Tester and Morrison 1990). The loss of molecular order was measured by the endothermic enthalpy of gelatinization. Many studies have been conducted to determine thermal properties of starches for different reasons, including the effect of lipid and protein on starch gelatinization (Hoover et al.,1993; Huang et al.,1994; Radosavljevic et al*.,*1998), the effect of amylose-lipid complexes (Tester and Morrison 1990; Morrison et al.,1993), the effect of annealing (Jacobs et al.,1995), and the effect of heat-moisture treatment on starch properties (Hoover and Vasanthan 1994). An and King (2007) came to the conclusion that ohmic heating conditions could alter thermal properties of rice starch and flours with varying proteins and fat levels, as compared to conventionally heated samples. In comparison to native CRS, onset and peak gelatinization temperatures of conventionally and ohmically heated samples were statistically higher Moreover, a significant decrease in enthalpies for all treated samples is due to

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the complete pre-gelatinization from conventional or ohmic heating so that they required less energy when they went through DSC heating .Compared to conventionally heated sample for 20 and 3.8 min, enthalpies of ohmically heated rice starch were lower at OH20V and OH40V, respectively. They further stated that a faster heating rate seemed to gelatinize samples less because of shorter cooking time, resulting in more energy being needed for gelatinization.

Wang and Sastry (1997) found that lower enthalpies by DSC means more starch gelatinization takes place beforehand so that less energy was needed for fully gelatinized starch than it did for raw samples. They also concluded that electrical conductivity changes synchronously with starch gelatinization. Data of %SG determined by DSC thermograms and conductivity curves match well in low and mid-gelatinization ranges.

Fernando et al.(2000) concluded that higher quantity of energy was required to gelatinize the native cassava and jicama starch relative to ohmically heated starches. The highest degree of gelatinization for jicama starch ($p \le 0.05$) was obtained with treatment 123 V-10 min and for cassava, 123 V-10 min. This corresponds to 70.03% gelatinization of the native jicama starch and 39.1% of cassava starch.

MATHEMATICAL MODELLING

Mathematical modelling of ohmic heating process and characterization of electrical conductivity of selected food materials have been done by several scientists (Davies et al, 1999; de Alwis et al.,1989; de Alwis and Fryer, 1990; de Alwis et al, 1992; Fryer et al.,1993; Khalaf and Sastry, 1996; Murakami and Ramanauskas, 1997; Orangi et al, 1998; Pa, 1991; Sastry, 1992; Sastry, 1995; Sastry and Palaniappan, 1992a, 1992b; Sastry and Li, 1996; Sastry and Salengke, 1998; Ye et al, 2003; Ye et al., 2004, Zhang and Fryer, 1993). Salengke and Sastry (2007) evaluated two hazardous situation, one involving static medium surrounding the solid and other involving a mixed fluid. A more conventional calculation of mixture cold-spot temperatures was indicated by mixed fluid model than the static model when the cold-spot occurs within the particle, typically occurring when the medium is more conductive than the solid. However, the static fluid model provides more conservative prediction of the mixture cold-spot temperatures when the cold-spot is within the fluid, particularly when the solid is more conductive than the medium.

To assess the role of fluid-particle heat transfer coefficient, parametric simulations were conducted using the model of Sastry and Palaniappan (1992), which is applicable to situations involving high solids concentration and mixed fluids. The results concluded that both average liquid and particle center heating rates increased as the fluid-to-particle heat transfer coefficient decreased. Marra et al. (2009) developed a mathematical model of a solid food material undergoing heating in a cylindrical batch ohmic heating cell. Temperature profiles and temperature distribution of the ohmic heating process were simulated and analysed via experimental and mathematical modelling. The simulation provided a good correlation between the experimental and the mathematical model. Optimization of the cell shape and electrode configurations and validation and ensurance of safe pasteurisation processes for other solid food materials could be done with the designed model.

A simple qualitative tool was developed from the data gathered by Mizrahi (1996), using simulation model, to analyse leaching losses during blanching,. The model is based on a process of unidirectional heat and mass transfer in an infinite plate. This model was formulated to allow for changing of medium and product volume, initial solute concentration in the product and in the medium, partition factors, plate and medium temperature, external heat and mass transfer coefficients and plate thickness.

Mathematical modelling of electrical conductivity for heterogenous materials was performed Zhu et al., (2010) using parallel, series, two forms of Maxwellï Eucken (ME-1 and ME-2) (Buonanno, Carotenuto, Giovinco, & Massarotti, 2003; Maxwell, 1954; Rocha & Cruz, 2001), and effective medium theory (EMT) (Landauer, 1952).

Salengke and Sastry (2007a,b) and Sastry and Palaniappan (1992a,b) executed mathematical modeling and experimental investigation of the case where a less conductive particle is surrounded by a highly conductive medium, which later on was ohmically heated under a static condition. They observed that the current passes through a more conductive medium and evaded the less conductive particle. Voltage drops and energy generation rates within both media are influenced by the presence or absence of alternative conducting paths through the surrounding medium.

Tumpanuvate T and Jittanit W (2012) develop the mathematical models for predicting the temperature changes of kinds of botanical beverages, concentrated juices and purees of orange and pineapple during ohmic heating. The temperature estimation of botanical beverages and concentrated juices were more accurate if the heat losses to the surroundings and evaporated moisture were included in the mathematical models.

ADVANTAGES

Its major advantages according to (Parrott, 1992) and (Castro et al, 2002):

1) Continuous production without heat-transfer surfaces;

2) Rapid and uniform treatment of liquid and solid phases with minimal heat damages and nutrient losses (e.g. Unlike microwave heating, which has a finite penetration depth into solid materials);
3) Ideal process for shear-sensitive products because of low flow velocity;
4) Optimization of capital investment and product safety as a result of high solids loading;
5) Reduced fouling when compared to conventional heating;
6) Better and simpler process control with reduced maintenance costs;
7) Environmentally friendly system.
8) Maintenance of the colour and nutritional value of food.
9) Less cleaning requirements.
10) Heating of particulate foods and liquidï particle mixtures.
11) Low risk of product damage due to burning.
12) High energy conversion efficiency.

DISADVANTAGES

Allen et al., 1996 compared the installation and operation cost of ohmic food processing systems to that of convetional retorting, freezing and heating in a conventional tubular heat exchanger and ohmic heating was found to be more costly than conventional methods for processing.

Another disadvantage is that the food containing fat globules are not effectively heated during ohmic heating process, as it is non-conductive due to lack of water and salt (Rahman, 1999). If these globules are present in a highly electrical conductive region where currents can bypass them, they may heat slower due to lack of electrical conductivity. Any pathogenic bacteria that may be present in these globules may receive less heat treatment than the rest of the substance (Sastry, 1992).

Also there is the possibility of ´runawayô heating (FDA-CFSAN, 2000). As the temperature of a system rises, the electrical conductivity also increases due to the faster movement of electrons.

FUTURE RESEARCH DIRECTIONS

Though enormous work on ohmic heating of different food materials has been done but this field requires some improvement or advancement in following areas:

1. Developing the knowledge necessary to compute the effects of electric field on mass transfer properties to optimize promising applications of ohmic heating.
2. Quantifying electrolytic effects during ohmic heating particularly the minimization of electrolysis at low frequencies at low frequencies, where several novel process options exist.
3. Modest experimentation on the influence of ohmic heating on microbial activity and inactivation has been executed. 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 intensely studied.
4. Deep understanding, characterization and modelling of electroporation phenomenon is required in order to optimize and utilize its effects.
5. More research is required to deal cold-spots identification and measurement during complex foods processing (e.g. multiphase foods).

6. Modelling, prediction and determination of the heating pattern of complex foods are also required to be evaluated 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.

CONCLUSION

Ohmic heating is an outstanding alternative heating process in which heat is directly dissipated into the food material rather than conduction or convection .The intense experimentation on the applications of ohmic heating in blanching, evaporation, extraction, sterilization, pasteurization and pre-gelatinization has been executed. Greater the electrical conductivity more is the ohmic heating. The rate of ohmic heating is enhanced with the increase in voltage gradient, ionic concentration whereas increase in particle size, thickness of electrodes results in reduction in rate of ohmic heating. Water holding and solubility index of flours and starches is improved with this process. Also the ohmic heating process leads to uniform heating, retention of better nutritional quality, high energy efficiency etc but higher cost input as compared to other conventional heating methods limits its commercial use on higher scale. Also the foods containing fats and oils cannot be processed with ohmic heating because of lack of salts and water. Though many developments has been made in this field but deep knowledge, regarding effects of electric field on mass transfer properties and process design to establish industrial processes, characterization and modelling of electroporation phenomenon, modelling, prediction and determination of the heating pattern of complex foods, is still lacking. In future, research should be emphasized in the area of characterization and modelling of electroporation phenomenon, complex foods. Experiments on cold spot determination should also be encouraged. Ohmic heating has a prospective for becoming the most important food processing technology in future.

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