OHMIC HEATING OF CABBAGE AND DAIKON RADISH AS AFFECTED BY SYSTEM PARAMETERS

By

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ABSTRACT

Ohmic heating was applied to aqueous solutions of two fresh vegetables: one leafy and one root vegetable for ohmic heating testing of two-phase food systems. Shredded cabbage (50% v/v) and daikon radishes cubes (57% v/v) as well as carrier fluid (0.15, 0.5, 1, 1.5, and 1.85% of salt solutions) were poured into a Teflon-coated static ohmic heating cell and heated at different constant voltages of 65, 80, 100, 120, and 135 V. The samples were tested from 30 to 70°C using low and high frequency with an alternating current of 60, 2070, 5030, 7990, and 10000 Hz. Voltage, current, time, and temperature were logged at selected intervals and used to calculate electrical conductivities as a function of temperature and to study the ohmic heating behavior of vegetables solutions. Of the vegetables examined, daikon radish gave the highest value for electrical conductivity (1.07 S/m at 30°C and 1.85%, 100 V, and 5030 Hz) and the shortest time to raise the temperature from 30 to 70°C: 6 min at 1.5%, 120 V, 7990 Hz and at 1%, 135 V, 5030 Hz. The general trend for cabbage solutions was that the magnitude of the electrical conductivity increased with increasing frequency at high voltage, but decreases at low voltage. An opposite trend was observed for daikon radish solutions: it increased with increasing frequency at low voltage, but decreased or remained the same at high voltage. For the heating rate of cabbage solutions, the magnitude increased with frequency at high voltage, but decreases at low voltage. On the other hand, for daikon radish solutions: it increased with frequency at both low and high voltages. Electrical conductivities and heating rates were found to increase quadratically with temperature in all cases. Electrical conductivities and heating rates were higher as the salt concentration and the voltage were increased for all vegetables studied. A slight slope change was observed in all cases between 50 and 60°C. As biological tissue is heated, structural changes occur: the cell wall suffers electroporation. The complete response surface models revealed that linear, cross products, as well as quadratic effects were significant. The observed ohmic heating behavior of vegetables solutions corresponded well with their electrical conductivity values. Regression analyses were significant for electrical conductivity and heating rates as a quadratic function of the sample temperature. It indicates the suitability of a quadratic model for electrical conductivity and heating rates changes with respect to temperature for all types of system parameters. The first Maxwell-Eucken model showed good agreement between predicted electrical conductivity values and experimental data, indicating its suitability.

RÉSUMÉ

Le chauffage ohmique a été appliqué à des solutions aqueuses de deux légumes frais: un légume-feuillu et un légume-racine pour des essais sur des systèmes alimentaires en deux phases. Le chou déchiqueté (50% v/v) et le radis daikon en cubes (57% v/v) ainsi que le fluide de support (0,15, 0,5, 1, 1,5 et 1,85% de solution saline) ont été versés dans une cellule statique de chauffage ohmique faite de Téflon et chauffés à différentes tensions constantes de 65, 80, 100, 120 et 135 V. Les échantillons ont été testés de 30 à 70°C en utilisant un courant alternatif de basse et haute fréquence de 60, 2070, 5030, 7990, et 10000 Hz. La tension, le courant, le temps et la température ont été enregistrés à des intervalles choisis et utilisés pour calculer la conductivité électrique en fonction de la température et étudier le comportement de chauffage ohmique des solutions de légumes. Des légumes examinés, le radis daikon a la plus grande valeur de conductivité électrique (1,07 S/m à 30°C et 1,85%, 100 V, 5030 Hz) et le temps le plus court pour élever la température de 30 à 70°C: 6 min à 1,5%, 120 V, 7990 Hz et à 1%, 135 V, 5030 Hz. La tendance générale pour les solutions de chou est que l'amplitude de la conductivité électrique augmente avec la fréquence à une tension élevée, mais diminue à basse tension. Une tendance inverse a été observée pour les solutions de radis daikon: elle a augmenté avec la fréquence à basse tension, mais a diminué ou est restée la même à haute tension. Pour le taux de chauffage des solutions de chou, l'amplitude augmente avec la fréquence à haute tension, mais diminue à basse tension. D'autre part, pour les solutions de radis daikon: elle augmente avec la fréquence à basse et à haute tension. La conductivité électrique et le taux de chauffage augmentent quadratiquement avec la température dans tous les cas. Les conductivités électriques et les vitesses de chauffage étaient plus élevées quand la concentration en sel et la tension étaient augmentées. Une légère modification de la pente a été observée dans tous les cas entre 50 et 60°C. Quand le tissu biologique est chauffé, des changements structurels se produisent: la paroi de la cellule subit une électroporation. Les modèles complets de surface de réponse ont révélé que les effets linéaires, produits croisés, ainsi que quadratiques sont significatifs. Les analyses de régression sont significatives pour les conductivités électriques et les vitesses de chauffage en tant que fonction quadratique de la température, indiquant l'aptitude d'un tel modèle pour tous les types de paramètres de système. Le modèle de Maxwell-Eucken 1 (ME-1) a démontré un bon accord entre les valeurs de conductivité électrique prédites et les données expérimentales, indiquant sa pertinence.

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This thesis is dedicated to my beloved parents, to my sister and brother for their blessings and love.

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CHAPTER 1

INTRODUCTION

With *Clostridium botulinum* as the target pathogen, sterilization of low-acid foods with particles is an important topic to the food industry. Thermal treatment either in cans or via aseptic processing using conventional heat exchange technology is the popular method since the early nineteenth century. Canning is known to end up with destruction of valuable nutrients and a loss of general quality of the food product, particularly for foods containing particulates (Ramaswamy and Marcotte, 2006). Ohmic heating is an alternative rapid heat transfer technique overcoming most problems associated with conventional heating techniques. An electrical current is passed through an electrically conducting food product for the heat generation: electrical energy is volumetrically converted into thermal energy. The electrical conductivity of the food material is the key property in this process as it controls the ohmic heating rate. The main disadvantage of conventional heating processing of particle-fluid mixtures is the over-processing of the fluid to ensure sterility at the centre of the particle as heat must first be transferred from the heating surface to the fluid before reaching the particle. Ohmic heating (also referred to as Joule heating, electroheating, electroconductive heating, and resistance heating) presents an interesting alternate by heating both phases at the same time by internal energy generation (Palaniappan and Sastry, 1991a). Ohmic heating has the advantage of eliminating the heat transfer surfaces and limiting conduction and convection heat transfer. This technique permits the food to be heated quickly and uniformly, with noold or hot spots, because both liquid and solid phases can be heated simultaneously, thus resulting in better energy gain (Allen *et al.*, 1996). Therefore, it is ideally suited to thermal processing of solid-liquid food mixtures with little structural, nutritional, or organoleptic changes and as well as those that are microbiologically safe and can be successfully treated using a short processing time (Rahman, 1999). The heating performance depends on the electrical conductivity of the matrix used (de Alwis and Fryer, 1992). The greatest preferred case in an ohmic heating process for particulate foods is that in which the electrical conductivities of fluid and solid particles are the same (Wang and Sastry, 1993). In this manner, close matching of electrical conductivities between phases is greatly desirable.

Although viewed as a promising food processing technology, ohmic heating has some technical limitations. Most ohmic heating systems have been used at an alternating current frequency of 50 to 60 Hz from the public mains supply. One constraint of the use of low alternating current frequency in ohmic heating is that electrolytic reactions can take place at the electrode surface, leading to product burning and corrosion of electrodes (Goullieux and Pain, 2005). Under alternating current conditions, the two electrodes (cathode and anode) interchange places according to the frequency. The electrochemical reactions of oxidation and reduction therefore occur alternately at the same electrode site. These reactions may be prevented by one of two approaches: 1) use of high-capacitance electrode materials, for example platinised titanium; or 2) use of high frequencies (Reznik, 1996). In both cases, the objective is to reverse the electric field before a double layer forms adjacent to the electrode, which produces Faradaic electrolysis. High capacitance electrodes work by increasing the time required for double-layer saturation, ensuring that electrolysis-free operation may occur at mains frequencies. The use of high frequencies ensures that the charge reversal occurs prior to double layer formation, regardless of electrode material. There have been some efforts to clarify the impact of frequency and waveform of alternating current on ohmic heating rates of solid or semisolid foods (Lakkakula *et al.*, 2004; Imai *et al.*, 1995; Lima *et al.*, 1999; Lima and Sastry, 1999).

Several studies nevertheless show that low-temperature long-time pre-treatment (LTLT) can improve the final texture of processed vegetables. In fruits and vegetables, the presence of pectic polysaccharides, which forms a major portion of the primary wall and also in middle labella between the cells, are mainly responsible for most of the texture (Jarvis, 1984). For particulate foods it has been noticed that most vegetables and meats have lower electrical conductivities than liquid (Tulsiyan *et al.*, 2007). Large vegetables, having a relatively small surface to volume ratio, can be blanched in a short time by ohmic heating without any need for dicing it first. The energy, dissipated by the electric current passing through the product, is capable of heating it uniformly and rapidly regardless of its shape or size (Mizrahi, 1996). A pre-treatment by salt infusion via soaking or blanching is often used to increase the electrolytic content within food materials and raise electrical conductivity (Palaniappan and Sastry, 1991a; Wang and Sastry, 1993).

Ohmic heating process is defined by several factors depending on installation (distance between electrodes, diameter of electrodes), process (voltage, current intensity, frequency, temperature, processing time) and product parameters (current avidity which induce the electrical conductivity value). The electrical conductivity is influenced by the product nature, meaning if the product is a good electricity conductor, also by temperature and by the magnitude of the voltage gradient. If the voltage gradient is high, the ohmic heating time is shorter and the temperature rises rapidly in close relation to the electric conductivity values (Nistor *et al.*, 2013). Nevertheless, selection of the operating conditions, such the electric field frequency, voltage, salt concentration infusion, end-point temperature, and treatment time should be carefully established.

The electrically produced damage linked to membranes electroporation should not be ignored (Wang and Sastry, 2002; Kulshrestha and Sastry, 2003; Sensoy and Sastry, 2004a). The mechanism of electroporation or electro-permeabilization is related to the accumulation of opposite charges on the two sides of electrically non-conducting cell membranes. Under the influence of the electric field, these charges move through the membrane. Additionally to the heating promotion, research data strongly suggests that the applied electric field under ohmic heating 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 and King, 2007; Lima and Sastry, 1999). The method has been employed in biotechnology for the inclusion of genetic material into living cells. Besides, membrane breakage comes along a meaningful increase of the tissue electrical conductivity and may affect the process of ohmic heating (Sarang *et al.*, 2007; Lebovka *et al.*, 2007a and b).

The objectives of the thesis work are:

a) to investigate the electrical conductivity and heating rate of fresh vegetables (cabbage and daikon radish) in the presence of salt solution ohmically processed under different system operating conditions (frequency of alternating current, voltage, salt concentration and temperature) and;

b) to establish suitable models for the electrical conductivity and ohmic heating rate.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW OF FOOD PROCESSING

Present day society has a need for novel food preservation techniques. Food is a biological material and is subject to degradative changes. The major cause of food wastage is the growth of micro-organisms. Physiological changes in the product and other chemical reactions also contribute to deterioration and nutritional losses. The conservation of a food product without deterioration requires both destruction of micro-organisms and enzyme inactivation. Enzymes act as biochemical catalysts that promote biochemical reactions in foods which cause deterioration. Enzymes are responsible for lowering both the sensory qualities (off-flavours and odours) and nutritional value (vitamin losses). The objective of food preservation is to extend the shelf life of food products, while maintaining the highest level of quality in aroma, colour, flavour, texture, and nutrient value. Processing of food is necessary for the preservation and storage of food materials. Many methods have been developed for food preservation, such as heating, freezing, drying, concentration, irradiation, salting and fermentation. Food preservation processes can act by creating an environment hostile to microbial, such as low water activity, low temperature, high concentration of solutes, low pH or combinations of these (e.g. drying, salting, concentration) or by directly destroying harmful micro-organisms (e.g. heat and irradiation) (Ramaswamy and Marcotte, 2006; Rahman, 2007).

Ohmic heating is non-traditional rapid method of heating that includes the employment of electricity. An alternating electrical current is circulated through a food product that serves as an electrical resistance. An electrical current is applied along or across the flowing fluid. The electrical power introduced into the product is converted into heat. As a thermal process, ohmic heating inactivates micro-organisms and enzymes by heat. Ohmic heating serves as an alternative to conventional heating techniques for food processing. Ohmic heating is also referred to as electrical resistance heating, direct resistance heating, Joule's heating, Joule effect heating, electroheating, electroconductive heating and electroresistive heating (Reznik, 1996). The clear advantage of ohmic heating over the traditional heat exchanger is the removal of the hot surfaces for heat transfer. The limiting heat transfer coefficient and the need for high wall temperatures are the main restraints of conventional heating. Along conventional thermal processing, either in cans or aseptic processing systems for particulate foods, important product quality damage may occur due to stagnant conduction and convection heat transfer. On the other hand, ohmic heating volumetrically heats the entire mass of the food material, thus the resulting product is of far greater quality than its canned counterpart. It is conceivable to process large particulate foods by ohmic heating that would be arduous to process using conventional heat exchangers (Ramaswamy *et al.*, 2005).

2.2 THERMAL PROCESSING OF FOODS

Thermal processing is the greatest ordinary unit operation in the food industry to preserve food systems since the development of the batch sterilisation technique by Nicolas Appert back in the 19th century. One of the bigger developments in thermal food processing has been the continuous high temperature short time (HTST) sterilisation process with its combined benefits of reducing the time operation at the same time than boosting the quality of the food products (Holdsworth and Richardson, 1989). Liquid foods or liquids with solid particles are being continuously processed, whereas solids remain heated in batch treatments. Along with the development of the continuous high temperature short time sterilisation process has evolved the technology of the aseptic processing. Aseptic processing is a high temperature/short time process that needs a continuous product sterilisation under appropriate quick heating, holding and cooling times, a package sterilisation autonomous of product sterilisation, an aseptic filling of the cooled sterile product into sterile packages at ambient temperature, and an aseptic sealing of packages (Woodroof, 1990). Liquid foods and liquid with solid particles foods of various viscosities are being continuously aseptically processed by plate, tubular or scraped surface heat exchangers (Marcotte, 1999).

Meanwhile, aseptic processing technology has been gradually taking the place of conventional in-can sterilisation for liquid foods in the food manufacturing. In-container sterilisation allows food to be kept at ambient temperatures for extensive periods, although the large magnitude of quality is lost because of the intense heating given to guarantee sterilisation of the food at the middle of the container. Aseptic processing technology has overcome lots of problems, such as low rate of heat penetration to the cold spot, long processing times, destruction of nutritional and sensory attributes, low productivity, and high energy costs (Mitchell, 1987; Smith *et al.*, 1990). However, other sorts of problems and inconveniences have been encountered with the aseptic processing technology. Aseptic processing of low-acid heterogeneous liquids having large particles is arduous due to mechanical damage as a consequence of blade scraping and unknown residence time distribution. Fouling has been a problem as a result of a deposit formation at the heating surface. The length of particles is restricted to 10-15 mm and only a portion of solids in the liquid of less than 30% is adequately processed because heat must be priory transferred from the heating surface to the liquid to then being able to extent to the particle. While the temperature of the liquid can be conveniently followed, it is unrealistic to get the temperature at the centre of the particle without meddling with the process. This requires over-processing of the liquid phase to make sure that the centres of the individual particles are sterilised (Parrot, 1992). Ohmic heating is an alternative rapid heat transfer technique to overcome most of the problems associated with the conventional heating techniques currently used in aseptic processing (Skudder, 1988).

2.3 DEVELOPMENT OF OHMIC HEATING PROCESS

The first application of the ohmic heating technology traced back to 1897 with Jones (1897) inventing an apparatus for sterilizing, preserving and purifying milk and other liquids by electrical or electrolytic action. The liquids were considered to be sufficiently good electrical conductors to cause the current to pass through the serpentine curve from one of the metallic side plates to the other. The entire volume of the liquid was subjected to a uniform current of electricity, thus causing the current to be diffused, to permeate and act upon every particle of the liquid. It was not until late 1920's, that a successful commercial technique, the Electro-Pure process, was introduced in the USA for the pasteurisation of milk (Andersen and Finkelstein, 1919). Within ten years thereafter, 50 industrial electrical milk sterilizers were in operation, but quickly disappeared in the 1950's (Getchell, 1935; Moses, 1938). A review of the Electro-Pure process reported later (de Alwis and Fryer, 1990a) revealed that the problems resulted mainly from improper contact between the electrodes and the food product. Electrolysis, product contamination, and adhesion of product to the electrodes were the problems which resulted from the use of unsuitable electrode materials. The development of the Elecster process for pasteurization of milk which is based on the Electro-pure came later and became an industrial achievement (Skudder, 1991). From 1930-1970, ohmic heating methods were experimented for vending applications for rapid heating of sausages, pizzas, and hamburgers. From 1950-1970, tests were done to apply ohmic heating for thawing purposes. Poor experimental results for complex solid geometry resulted from the difficulty in ensuring good contact between electrodes and the food. During the same years, ohmic heating researches to inactivate enzymes were performed on cut and peeled potato slices with the industrial process Osco. Continuous and rapid ohmic heating sterilisation techniques were not considered practical at that time without reliable aseptic packaging technology, adequate pumping technologies to prevent mechanical damage, and high level of control only made possible through the use of more recent computer technology. In 1980, a particular ohmic heating technology for fluids containing particulate foods was developed by the Electrical Council Research in Capenhurst, England. In 1983, it was licensed to APV Baker Ltd for commercial exploitation of the results (Simpson, 1980). Over 18 commercial industrial plants were installed, mostly in Europe, Japan, and the USA (Marcotte, 1999).

2.4 PRINCIPLES OF OHMIC HEATING

Ohmic heating occurs when an electrical current is passed through an electrically conducting product. An electrical current is the flow of free electrons from the electrical power supply through the conductor. These electrons result in frequent collisions with the atoms (or lattice ions) in the conductor, continually transferring their kinetic energy to these atoms. This causes the atoms to vibrate with greater energy, raising the temperature of the conductor. In this way, electrical energy (i.e., the kinetic energy of the free electrons) is converted into thermal energy through the vibration of the atoms. Since this energy is

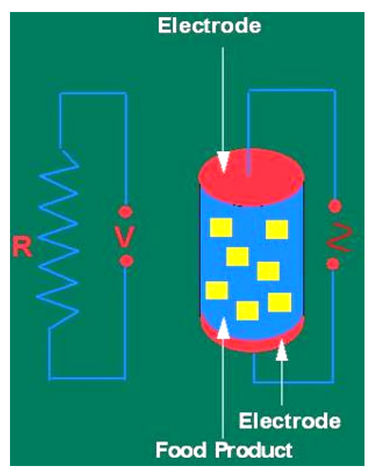


Figure 2.1. An electrical circuit analogue

converted into heat, the temperature of the conductor (and any parts of the experimental system with which the conductor is in thermal contact) will increase. Heat generation takes place volumetrically. This system is like an electrical circuit, which is made of a resistance and a source of voltage and current. The food product acts as the resistance when placed between two electrodes and the current passes through it; the food is therefore made part of an electrical circuit (Figure 2.1). Classical heat transfer mechanisms such as convection or conduction are minimal. A continuous (DC) or an alternating current (AC) may be employed. Electrical treatment may be carried out continuously or by rapid discharges pulses with or without any heat generation. The range of voltages for ohmic heating is between 3 kV and 12 kV while the range for high voltage impulses is between 14 kV and 35 kV (Barbosa-Canovas *et al.*, 1998). Pulsed electric fields and oscillating magnetic fields have been investigated as possible cold pasteurisation processes (Jayaram and Castle, 1992; Castro *et al.*, 1993; Pothakamury *et al.*, 1993).

The applicability of ohmic heating is dependent on product electrical conductivity. Ohmic heating is possible because most pumpable foodstuffs consist of water in excess of 30% and dissolved ionic species, such as salts and acids which make the material electrically conductive. Pure fats, oils, alcohols and sugars are not appropriate candidates for ohmic heating. These substances are electrically too resistive or in other words will not conduct sufficiently electrically to heat the product (Halden *et al.*, 1990; Mitchell and de Alwis, 1989; Palaniappan and Sastry, 1991a). Sarang *et al.* (2008) carried out conductivity measurements of meat cuts to show that lean meat is much more conductive than fat meat. Non-pumpable solid foods can also be processed by using a carrier conductive fluid, such as water and added conductive ingredients, such as salts and acids. The electrical conductivity of solid particles and carrier liquid should be closely matched for the heating rate to be similar. The particle to liquid ratio, the particle orientation (either parallel or perpendicular) in the field and the shape regularity of the particles were found to strongly influence the heating rate of the particle in the liquid (de Alwis *et al.*, 1989; Sastry and Palaniappan, 1992b ; Zareifard *et al.*, 2003).

As in microwave heating, electrical energy is converted into thermal energy in ohmic heating. However, ohmic heating draws in the dissipation of electrical energy by conduction into the food product as oppose to radiative energy transfer in dielectric material at high frequencies. Besides, unlike microwave heating, ohmic heating depth of penetration is virtually unlimited and the extent of heating in the ohmic heater is for the most part ruled by the spatial uniformity of electrical conductivity throughout the product and its residence time. As it heats, the food product does not demonstrate a large temperature gradient within itself, and liquid and particulates are heated virtually simultaneously (Biss *et al.,* 1989; Skudder and Biss, 1987). The necessity to over-process the liquid to guarantee sterility at the centre of a large particulate, as with heat exchangers, is hence diminished. This will result in the liquid phase to be less heat damaged and limit over-cooking of the external of the particulates. It may be possible to heat the midpoint of the particle even faster than the liquid (de Alwis *et al.*, 1989; Sastry and Palaniappan, 1992a). Accordingly, ohmic heating of liquids containing particulates could be looked at as an aseptic process of homogeneous liquids, which needs only the control of the liquid temperature (Larkin and Spinak, 1996). Various parameters and factors, affecting both the ohmic heating process and the food product being ohmically processed, need to be evaluated.

2.4.1 LETHALITY EVALUATION

Ohmic heating can be used for pasteurization and sterilization of food and other biological products. As in other cases implicating sterilisation, the crucial point is the prediction of cold-spot temperatures all along the process. The calculation of the processing time is done taking into account the necessity that a fixed achievement of lethality must be applied to the whole material. The lethality of a process is defined by the time that the food product is exposed to at a particular temperature and is governed by the integrated effect of temperature and time combination. For continuous tube flow aseptic processing, it is the accumulated lethality in the holding tube of an aseptic processing system and the processing temperature that is needed to be considered. The whole or integrated lethality is calculated utilizing the common F_o-value (Marcotte, 1999):

$$F_o = \int_0^t 10^{(T - Tref)/Z} \, dt \tag{2.1}$$

Where T is the temperature as a function of time (t) at the coldest location; T_{ref} is the reference temperature; Z is the negative reciprocal slope of the logarithmic thermal death time (TOT) or D curve versus T. The decimal reduction time (D) is the time for a reduction of micro-organisms by 90%. The goal is thus to find the coldest-location temperature to calculate the accumulated lethality sufficient to have a microbiologically safe food product. In the physical unfeasibility of temperature monitoring, as in continuous aseptic processing situation, biological evaluation is the backup to assess the lethality assigned at the cold point during ohmic heating (Weng *et al.*, 1991; Sastry *et al.*, 1988).

2.4.2 ELECTRICAL CONDUCTIVITY

The electrical conductivity or resistance of the food controls the ohmic heating rate. For this reason, the electrical conductivity is the fundamental property to be gathered for designing this process. The question is how conductive or resistive a food material should be in order to provide an appropriate heating rate and temperature increase. Highly conductive materials, such as metals, will allow an abundant flow of current and will result in lower rate of heating. Highly resistive materials such as wood, will allow an insignificant current to flow and result in limited heating as well. Therefore, it is mandatory to understand that in both theses cases, heat generation will not be adequate. In consequence, the values of electrical conductivity have limits within which a sufficient heat generation would occur. It would mean inefficiency of the heating process outside theses limits. Electrically too resistive substances (e.g. pure fats, oils, alcohols and sugars) as well as highly conductive materials (e.g. highly concentrated salt solutions) are not suitable materials for ohmic heating. Figure 2.2 demonstrates the operating region of electrical conductivities for a profitable ohmic heating process, within a maximal and physically definite power (de Alwis and Fryer, 1992).

De Alwis *et al*. (1989) stated diverse electrical conductivities from 10^{-3} to about 10^{2} S/m for a variety of food materials. Therefore, some food formulations have to be adjusted by mixing conductive and resistive food ingredients in order to have an appropriate overall electrical conductivity for the high efficiency of the ohmic heating process. The effect of temperature on electrical conductivity is well recognized for both liquid and solid food materials: as the temperature increases, the electrical conductivity increases too (Palaniappan and Sastry, 1991b).

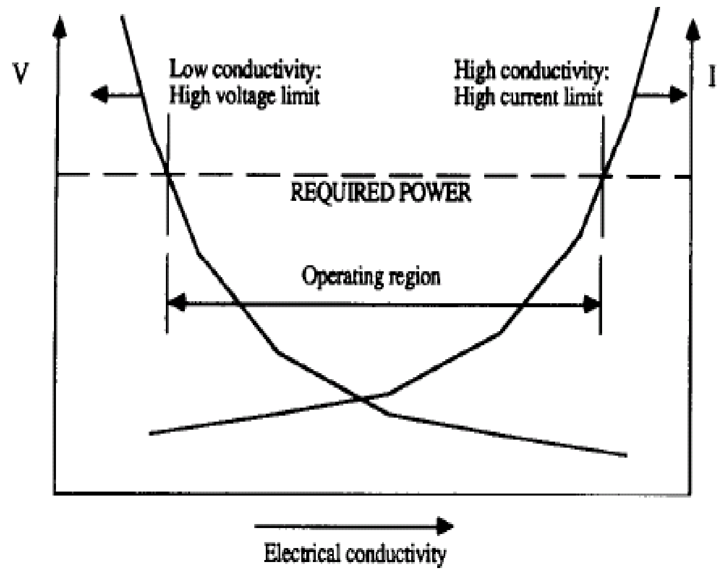


Figure 2.2. Bounded operating region of electrical conductivities (de Alwis and Fryer, 1992)

Electrical conductivities published values are for the most part determined at room temperature which is not the real temperature undergone by food during ohmic heating. Fryer *et al.* (1993) used an equation based on the electrical conductivity at 0°C to define the electrical conductivity profile of viscous liquids:

$$\sigma = \sigma_0 + K_T \, (T) \qquad (2.2)$$

Palaniappan and Sastry (1991b) expressed the relationship between electrical conductivity and temperature for liquids based on the electrical conductivity at 25°C:

$$\sigma = \sigma_{25} \, (1 + K_T \, (T - 25)) \qquad (2.3)$$

Where σ is the electrical conductivity (S/m); σ_0 or σ_{25} is the reference electrical conductivity at 0 or 25°C (S/m); K_T is the temperature constant (S/m °C); T is the temperature (°C). Figure 2.3 shows that the electrical conductivity temperature relationship is linear within a temperature range of 20 to 80°C for liquids and solid vegetable pieces in a liquid (Sastry and Palaniappan, 1992a; Fryer *et al.*, 1993).

Zareifard *et al.* (2003) observed the effects of particle concentration, size and location on heating and electrical conductivity behavior during ohmic heating of two-phase food systems. Palaniappan and Sastry (1991b) evaluated the importance of the effect of the percentage of solids although less important than the temperature effect. Sastry and Palaniappan (1992b) explained that the orientation effect increased as the solid-to-liquid electrical conductivity ratio increased. This fact is not relevant to situations drawing in long thin particles or large particle populations. The liquid electrical conductivity was reported to decrease with the increasing presence of solids, except for salt, or non-polar components scattered in the liquid phase. This can be explained by the fact that the electrical conductivity of solids is usually lower than the liquids one. Marcotte *et al.* (1998) presented response surface plots to demonstrate the effect of temperature and concentration on electrical conductivity of hydrocolloid solutions. The plots show clearly that electrical conductivity increased with temperature and concentration. As the concentration is increased, the effect of temperature is more important.

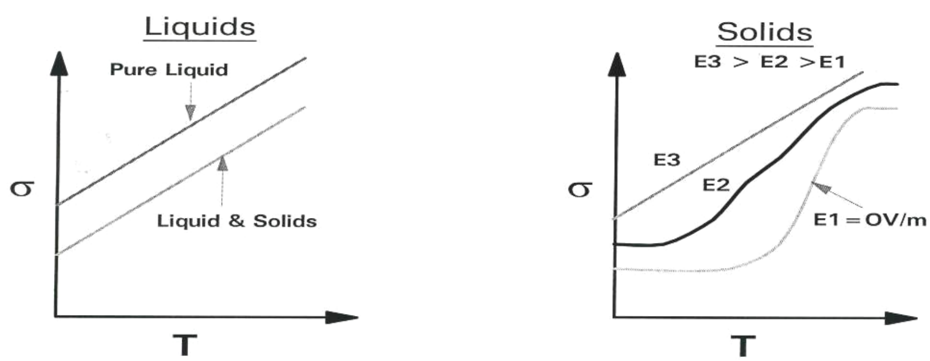


Figure 2.3. Electrical conductivities of solid and liquid foods
(Sastry and Palaniappan, 1992a)

Electrical conductivity values of raw vegetable samples demonstrate a sigmoid curve as a function of temperature with a typical slope change around 50°C caused by critical structural changes in the biological material (Figure 2.3). Eliot-Godéreaux *et al.* (1999) found no significant textural differences between cauliflower florets treated in a continuous ohmic heating pilot plant at 40 or 50°C and fresh samples, but the firmness of samples cooked above 60°C decreased. Eliot-Godéreaux *et al.* (2001) defined the optimal conditions for high temperature/short time sterilisation of cauliflower florets as low temperature pre-cooking in saline solutions, high flow rate and sufficient electrical conductivity. Wang and Sastry (1997) observed slope changes for electrical conductivity of raw vegetable samples (potato, carrot, and yam) when presented as a function of temperature. Values of electrical conductivity of raw samples were found to increase quadratically in the low temperature range (30 to 50°C) and then curves became linear thereafter. These slope changes might again indicate that critical structure changes occurred around 50°C. As vegetable tissue is heated, structure changes like cell wall breakdown, tissue damage and softening occur, affecting electrical conductivity. Falkenhagen (1934) first demonstrated that the electrical conductivity is a greatly dependent of the frequency for fluids with a high concentration of dissolved or entrapped ions. This was also confirmed by Imai *et al.* (1995) during ohmic heating of Japanese white radish. They found that 50 Hz gave the sharpest initial rise in temperature and the shortest time to raise the temperature below 50°C. Heating rates above 60°C were linear and similar for all frequencies studied. They found that heat generation was not the effect of dielectric loss but that it was due to the passage of the alternating current inducing electroporation of radish membrane and the derived reduction of its impedance.

The establishment of an ohmic heating process is abridged for homogeneous foods, but is arduous for heterogeneous mixtures. In this last case, it is the overall conductivity of the system that dictates the key operating conditions (Palaniappan and Sastry, 1991c). Measurement of electrical conductivity of two phase continuous flow systems is complex. The electrical conductivities of solid particles and carrier liquid should be as much as possible similar to have a uniform heating rate for the mixture. This perfect situation is not always doable, but it allows the easy monitoring of the liquid temperature only. When this happens, it would heat the middle of the particle faster than the liquid so that it would be sufficient to monitor the liquid temperature which is much easier to handle. To be able to do this, the electrical conductivity of the liquid should be adjusted to be lower than the solid one. Three physical parameters can affect the electrical conductivity: the voltage gradient, the distance between the electrodes (L) and the cross-sectional of the sample in the heating cell (A). The electrical conductivity (σ, S/m) can be determined from the resistance of the sample and the geometry of the cell using the following equation (Palaniappan and Sastry, 1991a):

$$\sigma = \frac{L}{AR} = \frac{LI}{AU} \tag{2.4}$$

Where L is the gap between two electrodes (m); A is the cross-section area of the sample in the heating cell (m^2); R is the electrical resistance of the product (Ω); I is current (A); U is voltage (V).

2.4.3 FREQUENCY OF ALTERNATING CURRENT

The frequency of the alternating current has an effect on the electrical conductivity of the product, the electrodes (electrolysis and polarization) and the food material (electroporation). Falkenhagen (1934) first demonstrated that the electrical conductivity is greatly dependent of the frequency for fluids with a high concentration of dissolved or entrapped ions. Alternating current at low frequency such as 50 or 60 Hz has an electrolytic effect comparable but lesser to that of direct current. The major electrolytic effect is the dissolution and corrosion of the metallic electrodes, which may contaminate the product. One way to overcome this problem is to use high frequency alternating current. At alternating frequencies above 100 kHz, there is likely no metal dissolution of stainless steel or titanium electrodes. Insoluble treated or coated carbon electrodes prevent direct contact and enable the use of more readily available electrical power at a frequency of 50 or 60 Hz from the public mains supply (Reznik, 1996).

When an electrical current is passed through an electrolyte bounded by metal electrodes, the accumulation of the ions at the electrodes produces the phenomena called polarization, which consists in electromotive force acting in the opposite direction to the current and producing an apparent increase of the resistance (Maxwell, 1954). This polarization during the ohmic heating process relies on several factors, such as the nature of the electrode surface and the frequency of the alternating current. It has been said that increasing the frequency of the applied voltage can reduce polarization. The effect of frequency is especially critical for the range of measured electrical conductivities (Cummings and Torrance, 1985). Additional non-thermal electroporation type effects have been reported at low-frequency (50-60 Hz), when electrical charges can build up and form pores across microbial cells (Ramaswamy *et al.*, 2005).

2.4.4 EFFECTS OF ELECTRICITY ON FOODS

Heat is known to cause physical, biological, and chemical changes during thermal processing. Possible physical changes are dehydration, cell rupture, tissue shrinkage, and loss of intercellular air and melting of fats. Possible biological changes are changes in membrane permeability, starch gelatinisation, pectin dissolution, and protein denaturation. Possible chemical changes are caramelisation, esterification, and Maillard reactions. Ohmic heating being most often a thermal process, these complex effects can clearly also occur but the nature and the intensity of the changes may differ. There also can be additional effects due to the imposed electrical field. Although ohmic heating is a heating process, it uses an electrical current through an electrically conductive food system for the heat generation. Hence, the electrical treatment of the food system may cause additional electrical effects on food systems (that includes micro-organisms and enzymes) mainly dependent of the frequency of the alternating current. There are four possible mechanisms in which electric fields can augment conductivity in ways impossible during conventional heating. Electro-osmosis, increase rate of plasmolysis, overcome diffusion limitation (increase the rate of ion transport between solution and cells) and increase in the diffusion flux across the membranes due to electrohydrodynamic mixing (de Alwis, 1990).

Solid foods as plant tissue are built on millions of individual cells cut off by the cell membrane and the wall. Dominant components of the cell membrane are phospholipids that can be compared to an electrical condenser. Electroporation appears when the applied voltage raises and brings about a membrane potential greater than 1 V while making perforations because of a potential discharge. At that moment, the encircling water will penetrate the cell because of osmotic pressure this will causes the cell to extend and break. Electroporation has been principally noticed under direct current conditions, but has also been seen with alternative current at high frequency of 10 kHz (Uemura and Noguchi, 1995).

Supplementary effects in foods like mass transfer have been found to happen due to the presence of an electric field. In an alternating current field, electro-osmosis happens because of the molecular diffusion (Wigerstrom, 1976). The rupture cell wall constituents like hemicellulose and protopectin often lead to the destruction of cell rigidity and intercellular adhesion, and will thereby influence food electrical conductivities. The loss of cellular arrangement shows higher conductivity due to increased ionic mobility. Also, an alternating current field can lead to an increase in diffusion across liquid membranes because of electrohydrodynamic mixing (Athayde and Ivory, 1985).

Microbial death by electricity can be provoked by mechanical, chemical or thermal effects (Palaniappan and Sastry, 1990; Bhat and Joshi, 1998). Microbial inactivation during continuous low-voltage alternating electrical studies has been assigned to heating (Palaniappan and Sastry, 1990). Enzymes are also inactivated by heat generation at low-voltage. Published results using high-voltage pulses in aqueous suspensions of micro-organisms stated a deep effect on the bacteria created by the electrical current (Mertens and Knorr, 1992; Barbosa-Canovas *et al.*, 1998). Under high voltage impulses, it is assumed that the damage is of mechanical type. Bacteria's death is induced by the creation of pores in cell membranes. The expected mechanism for pulsed electric field is the dielectric rupture theory that supposes that a critical transmembrane potential of about 1 V is acquired at precise field strength. In electro-hydraulic shock experiments, a rapid electrical discharge is applied to a suspension of micro-organisms without any heat generation. Subject to these surroundings, the decline in the number of micro-organisms was assigned to oxidation reactions (e.g. formation of hydroxyl, hydroperoxides, free radicals with oxygen, toxic metal ions from the electrodes and toxic chlorinated compounds) (Marcotte, 1999).

2.4.5 ADVANTAGES OF OHMIC HEATING

There are several advantages for ohmic heating (Biss *et al.*, 1989; Skudder and Biss, 1987; Parrott, 1992; Kim *et al.*, 1996; Reznik, 1996). Heating is very quick and a wide temperature gradient is not accomplished inside the food; therefore, heating is homogenous. There are no hot heat transfer surfaces and therefore less fouling on heat transfer surface and burning of the food product, resulting in minimal mechanical damage and better nutrients and vitamin retention. However, deposition phenomena onto the walls and electrode surfaces of ohmic heaters have been reported, acting as an additional electrical resistance causing an increase in the electrical power requirement. The ohmic process is perfect for shear-sensitive products: pieces are managed more softly and can keep up their completeness when compared with scraped surface heat exchangers. The process is made silent while operating due to the absence of rotating parts in the ohmic system. A large quantity of solids in liquid (50-80%) can be treated. It is similar to microwave heating without a connected action of converting electricity into microwaves before heating. Differently from microwave heating, the depth of heat penetration in the food is almost extensive. Energy conversion efficiency is very high because 90% of the electrical energy is converted into heat. It is even possible to heat the centre of the particle faster than the liquid, which is impossible for conventional heating. Ohmic heating of liquids containing particulates could be regarded as an aseptic process of homogeneous liquids, which requires only the monitoring of the liquid temperature. It is effortless to obtain a heating time/temperature profile to guarantee sterility because heat is generated within the solids without consideration for the liquid thermal conductivity. Eventually, the ohmic heater model could be seen as an independent product sterilisation process already including a holding tube assembly, pumping and cooling systems (Marcotte, 1999).

2.5 TECHNOLOGY OF OHMIC HEATING

2.5.1 DESIGN CONSIDERATIONS

Two dispositions of ohmic heater are available: This first one is a plate and frame arrangement where electrodes are placed between insulating plastic spacers. This configuration is also known as the transverse field mode (Stirling, 1987). The applied electric field and current flux are at right angles to the mass flow. The second configuration is a tubular heating column and is mainly used for particulate foods because of its internal clearance since electrodes are inserted into an electrically insulated tube (Skudder, 1988). This configuration is considered collinear: the applied electric field and the current flux are parallel to the mass flow (Stirling, 1987). These arrangements will determine the heating behavior and the flow pattern. The design of a continuous ohmic heating column is mainly determined by the selected configuration of the system, the heating rate, the flow rate, and the desired temperature rise of the food product (Reznik, 1996).

A power unit generates the necessary electrical field at the electrodes. It includes: a variable transformer, an isolation transformer, a voltage transducer, a current transducer, power relays, and fuses. By applying suitable alternative current potentials from a controlled power supply to each electrode, current is caused to pass through the moving product as it flows through the heater. The ohmic heater assembly can be seen in the context of a complete product sterilisation or cooking process where there is already a holding tube, pumping, and cooling systems. The column is mounted in a vertical position with the flow of product in an upwards direction. A vent valve located at the top of the heater guarantees that the column is always full. The column is made such that each heating section has the same electrical impedance and hence the interconnecting tubes generally increase in length towards the outlet. This is because the electrical conductivity of food products usually increases with increase in temperature: actually for aqueous solutions of ionized salts there is a linear relationship between temperature and electrical conductivity (Parrott, 1992). Heating occurs in the different sections between two electrodes. The food is then held in the holding tube for temperature equilibration between the liquid and solid before being cooled in tubular heat exchangers. Commercial ohmic heating plants are ready for use with a fully automatic temperature control system. Inlet changes such as modifications in inlet temperature, mass flow rate, and product specific heat capacity will influence the final product outlet temperature.

A microprocessor in the control system generally controls these variables and regularly calculates the electrical power required to heat the product and correlates this value with the signal from a power transducer on the output side of the transformer. Feedback monitoring is employed to avoid a long term drift in outlet temperature (Parrott, 1992). Commercial APV ohmic heating equipments are arranged particularly to connect with a continuous process line. As an example, a 30 kW unit is required to process up to 300 kg/h and 600 kW units are employed for 6000 kg/h of food product. For laboratory purposes, a 5 kW pilot plant scale unit is required for a single batch of 50 kg or it can be conducted in a continuous mode of 50 kg/h. The power for pilot scale units is 10 kW for a continuous production of 100 kg/h (Marcotte, 1999).

2.5.1.1 HEAT GENERATION, HEATING RATE, AND TEMPERATURE RISE

The local internal electrical heat generation rate in a ohmic heater is calculated using Ohm' s law for constant voltage (Marcotte, 1999):

$$\dot{Q} = E^2\sigma = (\nabla V)^2\sigma \tag{2.5}$$

where $\nabla V = \mathrm{E}$ is the voltage gradient (V/m) or electric field intensity and σ is the local electrical conductivity. The ohmic heating rate is calculated from the electric field, electrical conductivity, density, and specific heat of the food product. Therefore, the heating rate depends largely on the physical properties of the food, more specifically on the electrical conductivity. In the absence of other significant heat transfer mechanisms such as convection or/and conduction, neglecting heat losses to the surroundings and using constant voltage conditions, the heating rate can be calculated (Marcotte, 1999):

$$\frac{dT}{dt} = \frac{\sigma(\nabla V)^2}{\rho\,\mathrm{C}_p} \tag{2.6}$$

The temperature rise in each section of an APV continuous ohmic heater tube (Skudder and Biss, 1987) was calculated by:

$$\Delta T = \frac{V^2\,\overline{\sigma}\,A}{L\,\dot{m}\,\mathrm{C}_p} \tag{2.7}$$

The temperature rise (temperature of the product at the heater entrance and exit) determines the power requirement.

2.5.1.2 ELECTRICAL POWER, TOTAL CURRENT, AND CURRENT DENSITY

The required electrical power, which will determine the size of the transformer, is estimated from the product mass flow rate and the specific heat knowing the inlet and outlet temperatures (temperature rise) desired (Marcotte, 1999):

$$P = \dot{m}\, C_p (T_{\text{out}} - T_{\text{in}}) \qquad (2.8)$$

Where $\dot{m}$ is the mass flow rate (kg/s); C_p is the specific heat (J/kg °C); (T_{out} - T_{in}) is the temperature rise (°C). The power requirement (heating requirement) will determine the maximum flow rate. Once the power is known and with given constant voltage, the total current can be determined using standard electrical relationships (Marcotte, 1999):

$$P = VI = RI^2 = \frac{V^2}{R} \qquad (2.9)$$

The next factor to be considered is the current density. This is one of the most important parameters. By definition it is the current divided by the area of the electrode. All products have a specific critical current density above which arcing is likely to happen. Therefore, the limiting current density is recognized and the total current determined by already known power and voltage, and the minimum area of the electrode is determined. Because all of the above mentioned parameters are linked, there are no choices, and the geometry of the device for the specific utilization is selected. Changing geometrical dimensions will need a change in other parameters. The geometry determines the resistance, which in turn determines the current. For example, decreasing the distance between the electrodes will also decrease the resistance, which will increase the current to maybe beyond the maximum critical value, which fatally may lead to arcing. Correctly, a low total current should be utilized, requiring a high resistance, which in turn commands a small cross-sectional area and/or a long distance between the electrodes. If one would be to change the distance without changing the area, it would increase the resistance and volume between the electrodes, but would accordingly decrease the power, which means that the temperature would not rise to the desired level. Using the relatively low voltage of standard power line will need high currents to attain the required power. It is important to respect the maximum current limitations. That is why the use of correct transformers is prudent in order to increase the voltage and allow the use of low currents. Common available transformers can provide up to 12 000 V at various power levels. The power specification of the transformers should be about 30% higher than the power requirement to make up for changes in power demand. Transformers have limitations on current, and these command the selection of the optimal resistance, which in turn dictates the geometry of the ohmic heater. That is why if the resistance is too high, the current at the maximum voltage will be too low and the power will be too low too. On the other hand, if the resistance is too low, the maximum limiting current will be reached at low voltage, and the power will be low. To make the best use of the available power, the conductivity of the product has to be evaluated and cautiously integrated in the design (Reznik, 1996).

2.5.1.3 FREQUENCY OF ALTERNATING CURRENT AND CURRENT DENSITY

As compared to the current, the frequency of the alternating current offers less flexibility. Most often, it comes from a public utility at 50 or 60 Hz. It is understood that electrolysis effects happen at these low frequencies for direct and also alternating currents. Using higher frequency AC could prevent this problem as well as the dissolution of metallic electrodes (Reznik, 1996; Remik, 1988). For alternating current, the maximum safe current will rely upon the current density, a property of the electrode material and geometry. Following one of Faraday's law, the extent of chemical change coming from the flow of direct current across an electrode/solution interface is proportional to the quantity of electricity passed through an electron-transfer process. Nonetheless, alternating current flow can happen through a non-electron transfer without electrolysis because of the presence of ionic double layers at the interface electrode/electrolyte (Crow, 1979). The electrostatic lining up of dissolved solution ions with the electrode surface of opposite charge is assembled like a capacitor. Therefore, the only way by which the flow of an alternating current can occur is by charge migration. This capacitive double layer can barely hold up a define maximum of alternating current density before a sufficient voltage is reached before producing electrochemical reactions. This maximum safe current density must be chosen for the specific electrode material. A safe working maximum of 8000 A/m^2 was deduced with less than

0.1% Faradaic current. A maximum of 4000-5000 A/m^2 is if common use for design matters (Stirling, 1987).

2.5.1.4 ENERGY EFFICIENCY

The overall energy efficiency (ε) of the ohmic heating process can be determined by the specific heat energy (SHE), making the assumption that the specific heat of the product remains constant throughout the process, and by the specific electric energy (SEE) consumption with heating time (t) for the mass of product (M) as a function of the constant voltage (V) and the varying current (I) measured (Huang *et al.*, 1997). The relationship is the following:

$$\varepsilon(t) = \frac{\mathrm{SHE}(t)}{\mathrm{SEE}(t)} = \frac{\mathrm{C}_p(T(t) - T_0)}{\int_0^t \frac{V\, I(t)}{M}\, dt} \tag{2.10}$$

At low temperatures, all the electrical energy is converted to heat. As the temperature increases, the efficiency decreases linearly.

2.5.2 RHEOLOGICAL PROPERTIES

The rheological properties of the fluid are needed for fluid mechanics studies in order to distinguish the flow nature as the fluid travels through the continuous ohmic heating system (Holdsworth, 1971). The type of fluid and its rheological properties will impact the velocity profile in the ohmic heating pipe (Steffe, 1992). Flow regime specification (laminar, transition or turbulent) requires the calculation of the Reynolds number which is a measure of the ratio of the inertial force to the force of internal friction (viscosity). The rheological behavior of matter that flows is characterized by the measurement of viscosity that is defined as the internal friction or resistance experienced by the fluid as it moves over another layer of the fluid. In ohmic heating, the rheological behavior of matter will change during the process as the electrical conductivity of the specific product increases as the temperature rise.

2.5.3 RESIDENCE TIME DISTRIBUTION

The residence time distribution (RTD) of a two-phase flow system is important in the establishment of the thermal process. The residence time distribution is defined as the length of time that elements spend in a system. Moving heterogeneous phases in a pipe will end up in a residence time distribution in both liquid and solid phases (Manson and Cullen, 1974). It happens that particles move faster than the average velocity of the liquid. In this case, the fastest moving particle can dictate the process design (Lee and Singh, 1990). Marcotte *et al.* (2000) assessed the residence time distribution of particulate foods during ohmic heating using an ultrasonic method. Variations of sound attenuation were found to illustrate well the residence time distribution.

2.5.4 VELOCITY

The energy in ohmic heating is added by the electrical current, which flows at the speed of light. The velocity and the resulting turbulence in common systems promote quick mixing and then improve heat transfer by keeping up a maximal temperature gradient. In a perfect ohmic heating of homogeneous fluids, it lacks a temperature gradient because the temperature is the same beyond the cross-section of flow. The velocity of the homogeneous product is negligible as compared to the one of the electrical current, and the current flows as if the product was absent. However, when the velocity of a heterogeneous product is not the same in the cross-section, the residence time of the slower moving fluid in the ohmic heater is longer. As the heating rate increases, it becomes more important to minimise differences in velocity in the cross-section. The velocity of the food product in the ohmic heater is a key parameter for applications with a high temperature rise. When the material or part of it solidifies or evaporates, arcing may happen. When material solidifies, it may become overheated and reduce the flow rate while increasing the resistance. This in turn may result in boiling of the liquid at the electrode, and bring arcing. For that reason, it is mandatory to design the process to result in a turbulent flow and to keep the system pressure well above the boiling point (Reznik, 1996).

2.5.5 FLOW BEHAVIOR

The flow of a food product in a pipe can be characterized as laminar, turbulent or plug type. Laminar flow is commonly defined by a Re number smaller than 2100. The arbitrary range defining the transition zone at which the flow regime changes from laminar to turbulent is between Re numbers of 2000 and 3000. All particles flow at the same rate as a uniform entity with a flat velocity profile in plug flow. The velocity profile of a Newtonian fluid in laminar flow is parabolic shaped with the fastest particle at the centre of the pipe. Its velocity is about twice the average velocity of the entity. For turbulent flow, the fastest element is also at the centre of the pipe but at 1.25 times the average velocity. The flow regime specification is determined through the rheological properties of fluids (Marcotte, 1999).

2.5.6 WORST CASE SCENARIO

Factors affecting the flow and heating behavior have to be analyzed while formulating an ohmic heating process (Sastry, 1991). Electrical conductivities of solid and liquid phases and their temperature coefficients should be carefully paired. If this is not possible and that the solid phase is of lower electrical conductivity than the liquid phase, particle concentration is of great importance. The lowest electrical conductivity particle in the mixture should be identified as a potential candidate to result in under-processing. Thermal process calculation for ohmic heating should always be based on the worst case scenario. Sastry and Salengke (1998) defined the worst case scenario as being the situation within which a single particle is of lower temperature than the surroundings. This would occur when there is an inclusion particle of lower or higher electrical conductivity.

A particle aligned parallel to the electrical field while allowing a maximum current by-pass and having a minimal cross-sectional surface area exposed to the current will heat more slowly. The particle orientation has more importance as the shape of the particle gets more irregular. The effects are insignificant for cubic and spherical particles. Particle size has a small effect on heating rates. Residence time distribution and fluid-to-particle heat transfer coefficient have effects that are less significant than in conventional processing. Ultimately, the residence time distribution of the fastest particle should be employed to set up the worst case scenario in thermal process calculation in order to prevent the current by-pass scenario and the resulting under-processing (Sastry, 1991). For that undesirable case, convection should be contained in the calculation model. Differently from conventional heating where fluid motion is necessary for improving heating, internal heat generation processes have the potential for runaway heating at selected locations and fluid motion has the effect of dissipating the heat and serving to moderate the heating rather than enhancing it (Sastry and Salengke, 1998).

2.6 APPLICATIONS OF OHMIC HEATING

2.6.1 BLANCHING

Mizrahi (1996) evaluated blanching of beets by ohmic heating and heating in a water bath. Whole, diced or sliced beets were immersed in an aqueous medium between two electrodes having no direct contact with the product. These electrodes were connected to an AC voltage source (380 V), whereby current was passing through the product via that liquid medium. To obtain a uniform heating, the initial specific electrical conductivity of that medium was adjusted, by adding salt solution, to have the same value as that of the product. Boiling temperature in both the medium and the sample was reached in less than 30 s. Blanching of large and irregular shaped vegetables by ohmic heating is done in relatively short time. Large vegetables, having a relatively small surface to volume ratio, can be blanched in a short time by ohmic heating without any need for dicing it first. The energy, dissipated by the electric current passing through the product, is capable of heating it uniformly and very fast regardless of its shape or size. In contrast, dicing is required in order to maintain a reasonably short water-blanching time. Leaching of solutes during blanching follows the same pattern regardless of the heating method: it is practically linearly proportional to the surface to volume ratio of the product and to the square root of the process time. A reduction of one order of magnitude in solutes losses may be achieved when blanching large and irregular shaped vegetables by ohmic heating due to a favourable combination of low surface to volume ratio and short process time.

2.6.2 GELIFICATION

Huang *et al.* (1997) studied ohmic heating to coagulate protein from proteinaceous liquids using wash water of frozen fish mince. During thermal treatment process, heat was supplied to raise the temperature of waste water and cause heat-sensitive proteins to coagulate and precipitate. The batch-type ohmic heating apparatus used consisted of a stirring bar and two stainless steel electrodes in a beaker on a magnetic stirrer. To prevent heat loss, the beaker, covered with a plastic lid, was enclosed inside a styrofoam box. At constant voltage of 90 V, the temperature of wash water samples was raised to different set points. After reaching a selected set point, the temperature was held constant.

Effects of heat and holding time on protein coagulation, kinetics of coagulation process, apparent electrical conductivity and energy consumption were investigated. At the early stage of heating, almost all electric energy was converted to heat energy. As the temperatures rose, energy efficiency began to decrease linearly with the temperature. Recovering fish protein from waste water can not only reduce the negative environmental impacts and costs of waste disposal, but also may generate potential profits if the protein can be utilized. Ohmic heating was employed as a rapid method of heating and was found to maximize gel functionality as compared to conventional heat treatment where as protein coagulates, a considerable amount of proteins is deposited on the surface of the heating walls, increasing the heat transfer resistance.

2.6.3 THAWING

Robert *et al.* (1998) designed and tested an automated computer controlled prototype ohmic thawing unit to thaw frozen shrimp blocks without hot spot formation. With the current flowing through the thawed portion of the block, enough heat is generated to cook the shrimp in that portion, while the rest of the block is still frozen. This is called runaway heating, or the formation of hot spots. This occurs because electrical conductivity of frozen food is about two orders of magnitude lower than that of thawed food. Localized heating could be monitored at one surface only because hot spots occur simultaneously on both surfaces of the block. The frozen shrimp block was placed between a pair of electrodes. The top and bottom electrodes were divided into four equal quadrants electrically isolated from each other by a silicone coating. Each quadrant had 32 thermistors connected to an electronic circuit board. Signals from the thermistors were continuously compared by the board to a dial-adjustable set point temperature above the melting point of shrimp and well below cooking temperatures. If excess temperature was detected at the surface of one quadrant, its power was shut off while the other quadrants continued heating the block. The computer monitored the maximum current passing through any quadrant and adjusted the voltage output of the variable transformer. The operation needed relatively high voltage levels at the beginning with relatively low current passing through the block since electrical resistance of the block was high. As heating continued, the temperature of the block increased and its resistance decreased. The advantages of this ohmic thawing unit are: no water used in the process and no wastewater generated, thawing time is shorter than water thawing, the process is easy to control, and thawing is relatively uniform due to volume heating.

2.6.4 STERILIZATION

Benabderrahmane and Pain (2000) created a model simulating thermal behavior of a solid-liquid food mixture flowing in an ohmic heating sterilizer. The behavior of solid-liquid systems sterilized in an ohmic heating column is very complex. The model attaches importance to the thermal diffusion in particles flowing in the column and to the particle-liquid slip velocity. A study was done on the effect of mean slip velocity on the thermal behavior of the mixture, taking into account the convective heat transfers between the two phases, the conductive transfers inside the particles, the sensitivity of the electrical field on the particle presence, the effect of the delivery solid volume fraction and the particle/tube diameter ratio. For a mixture with homogeneous electrical conductivity, an increase in the slip velocity or mixture volume fraction induced, at the tube outlet, a more important heating of the particles as compared to the liquid and also caused a higher temperature gradient in the particle. A greater sterilisation in the particle centre was thus obtained. The process critical point was, unlike in traditional processes, situated in the liquid and not in the particle. The model demonstrated the influence of the inhomogeneous electrical conductivities on heating of the food materials and its great impact on the sterilisation efficiency.

2.6.5 PASTEURIZATION

Zareifard *et al.* (2003) observed the effects of particle size, concentration, location, and temperature on heating behavior and electrical conductivity during ohmic heating of two-phase food systems. Carrot-starch mixtures were treated in a static Teflon ohmic heating cell. A constant voltage of 250 V was applied and the maximum current was 10 A. Three particle sizes were considered: carrot puree, considered as 0 mm particle size, and 6 and 13 mm cubes. Experiments were conducted with 30, 50, and 100% w/w solid concentration. A second set of experiments was also carried out using a wider range of particle concentrations (6-mm cubes) from 0 to 60 at 10% increments. The liquid phase was 4% starch solution with 0.5% w/w salt. The particle locations were compared: in parallel, in series, and in well-mixed conditions with the liquid phase with temperature ranging from 20-80°C. A very thin metal mesh separator was used to keep the solids in place.

It was observed that the heating time increased along with particle size and concentration. The electrical conductivity increased with the process temperature and decreasing as particle size or concentration increased. With respect to the particle location within the ohmic cell, the thermal behavior was different when the two phases were in parallel, in series or in mixed condition. However, there was no significant difference between overall values of electrical conductivity when liquid and solid phases were separated as compared with the mixed condition.

2.6.6 EXTRACTION

Lakkakula *et al.* (2004) used ohmic heating to stabilize rice bran and to improve rice bran oil extraction yield as compared to microwave heating and a control (no heating). Rice bran is a component of raw rice that is obtained when it is removed from the starchy endosperm in the rice milling process. It is high in oil content (15-25%) and has low moisture content (6-7%). Rice bran is a waste product in the milling process but it has a potential to be used as oil source. Three electrical field strengths (60, 100, and 140 V/cm), three moisture contents (10.5, 21, and 30%) and two frequencies (1 and 60 Hz) were tested on a laboratory-scale ohmic heater equipped with two titanium electrodes. The 10.5 % moisture content samples were heated for 15 min (resulting in a final temperature increase of less than 1°C) and in the case of moisture added samples (21% and 30%), the bran was heated until a temperature of 105°C was reached. The bran was cooled to room temperature and oil was extracted immediately using a hexane extraction procedure.

Results showed that ohmic heating is an effective method for stabilizing rice bran with the addition of moisture, which enables heating over 100°C to occur. Ohmically heating rice bran without the addition of moisture is not an effective stabilization method. The low electrical conductivity of the bran does not allow the temperature of the sample to increase. Increasing the electrical field strength from 60 to 100 V/cm increased the extraction yield for all moisture contents. Increasing the electrical field strength from 100 to 140 V/cm did not significantly increase the amount of oil extracted (it slightly decreased at 30% moisture content). This suggests that there exists optimal electrical field strength for extraction, and providing higher field strength beyond this optimum does not significantly impact the amount of oil extracted. Ohmic heating using an alternating current of 1 Hz yielded significantly more oil than ohmic heating conducted at 60 Hz for all moisture levels. Electroporation effects may be more pronounced at lower frequencies due to the increased time that cell walls are exposed to alternating current, which allows the cell walls to build up charges and form pores. Free fatty acid (FFA) 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.

2.6.7 HIGH-FREQUENCY SHORT PULSE – COLD TREATMENT

Samaranayake *et al.* (2005) examined a pulsed ohmic heating technique to determine its effect on electrochemical reactions as compared to conventional 60 Hz sinusoidal ohmic heating. In ohmic heating, chemical reactions at electrode-solution interfaces induced by current are considered potentially undesirable. Corrosion of electrodes and apparent electrolysis of the heating medium are often encountered in ohmic heaters powered by low-frequency alternating currents of 50 to 60 Hz. Electrolysis is the decomposition of a chemical compound brought about by the passage of an electrical current through the compound or a solution containing the compound. Electrochemical phenomena at electrode-solution interfaces can be suppressed by using high frequency alternating currents. However, the use of high frequency generators, especially for industrial scale ohmic heating, may be limited by cost considerations. A scale batch ohmic heater was used for both pulsed and conventional ohmic heating experiments. For pulsed ohmic heating, the ohmic heater was connected to an insulated-gate bipolar transistor (IGBT) power supply that was capable of delivering bipolar potential pulses. The IGBT power supply had a fixed peak voltage of 170 V with switching frequency up to 10 kHz. To study the effects of frequency and pulse width, two switching frequencies, 4 and 10 kHz, were therefore chosen, representing both upper and lower frequency ranges. The delay time between bipolar pulses was varied. Effects of pulse parameters, such as frequency, pulse width, and delay time were studied, in comparison with conventional ohmic heating using various electrode materials (stainless steel (316), titanium, platinized-titanium, and graphite). Analyses of electrode corrosion, hydrogen gas generation, and pH change of the heating media were performed. Concentrations of Fe, Cr (from the stainless steel electrodes), Ti (from the titanium electrodes), Pt, Ti (from the platinized-titanium electrodes) and elemental carbon (from the graphite electrodes) migrated into the heating media were taken as measures of electrode corrosion. Initial pH of 3.5 (at 25°C) was specifically chosen, because it is the pH of the worst-case scenario for all electrode materials with respect to corrosion.

For stainless steel electrodes, pulsed ohmic heating at higher frequencies and shorter pulse widths yields the lowest rates of electrochemical reactions. However, pulsed ohmic heating at lower frequencies and longer pulse widths is more effective in suppressing the electrochemical reactions of titanium and platinized titanium electrodes, while achieving higher duty cycles (pulse widths/period). In general, except at the highest frequency, low duty-cycle heating, pulsed ohmic heating was less successful in suppressing the electrochemical reactions of graphite electrodes compared with conventional ohmic heating. Delay time was found to be a critical factor in pulsed ohmic heating. The sufficiency of a given delay time is dependent on the symmetry of positive and negative pulses of the pulse waveforms. The importance of allowing enough delay time for discharge of the electrical double layers after each pulse input is emphasized. Conventional ohmic heating provides its best results for graphite electrodes. However, in all cases, it is possible to identify a pulsed ohmic heating treatment that was superior to conventional treatment in terms of minimization, in some cases, to undetectable levels by use of IGBT pulse inputs of electrochemical reactions.

2.6.8 IN-CONTAINER STERILIZATION

Jun and Sastry (2005) modeled and optimized pulsed ohmic heating for chicken noodle soup and black beans reheating and sterilization inside a flexible package to minimize the equivalent system mass during long-duration space missions. A package made of flexible pouch materials was powered through a pair of metal foil electrodes extending out to permit ohmic heating. The multilayered laminates flexible packaging provides an alternative to the rigid container. The electrode assembly made of aluminum foil is placed between a folded laminate, with the electrodes extending out and heat-sealed on the edges. A specially designed ohmic heating enclosure was built to place the flexible package in contact with the external electrical circuit. The package has the potential to be reused after food consumption. The objective was to optimize electrode configurations in the pouch to yield the most rapid and uniform heating thermal profiles. Three different electrode configurations (Pouches A, B, and C) were designed. Pouch A had one electrode (2 cm in width) on the top left and the other (2 cm in width) on the bottom right of the package, while Pouch B had V-shaped electrodes (3 cm in width) at each end. Pouch C had one electrode (2 cm in width) on the top middle and the other two electrodes (1 cm in width) at each end on the bottom. A 2-D thermal-electric model with simplified parameters was developed to optimize the design and layout of electrodes to ensure uniform heating of the material. Modeling of ohmic heating of liquid-particulate mixtures is difficult because of various unknown factors such as different electrical conductivity, particle size, shape and orientation to the electrical field. A static system under the assumption of there being neither fluid motion nor natural convection in a microgravity environment was implemented. The temperature distribution was determined according to a particular equation and the electric field distribution within an ohmic heater was calculated by solving Laplace's equation. The initials conditions and the electrical and thermal boundary conditions were determined. The governing equations were solved using the commercially computational fluid dynamics (CFD) software Fluent. Paved triangular meshes of the geometry for packages with the three different electrode configurations were constructed using the Gambit 2.0 preprocessor (Fluent, Inc., Lebanon, NH). Through mesh refinement study, the optimum numbers of mesh elements for Pouches A, B and C were 468, 1048 and 924, respectively. For model verification (validation), temperature values were measured at seven different locations inside the package with one unsealed end. A critical issue was to install and maintain the thermocouple probes at fixed locations during heating because the packaging material is flexible. The pouch was powered by the ohmic heater with high-frequency pulsed alternating current. The power supply was developed to generate the square waveforms with frequency of 10 kHz and duty cycle (pulse widths/period) of 0.2. The thermal behavior predictive accuracy was typically lower at each end of the package, wherein the electric field strength is weakened. This might be because of localized non-uniformity between the two phases. Unlike electrodes in parallel, the pouch electrodes were found to induce the overshoot of voltage gradient on the edges. Pouch B with V-shaped electrodes had the lowest ratio of cold zone area to the entire package area and was therefore expected to be more likely to perform uniform heating within the package.

2.7 MODELING

2.7.1 MODELING OF ELECTRICAL CONDUCTIVITY

The efficiency of ohmic heating is dependent on the conductive nature of the food to be processed and hence the knowledge of the electrical conductivity of the food as a whole and its components is essential in designing a successful ohmic heating process. The electrical conductivity behavior of particle-fluid systems is important for better understanding of heating behaviors in ohmic processing of particle-fluid food systems. For the effective thermal conductivity calculation of two-component material systems, five theoretical models were established to better understand electrical conductivity variation of various solid-fluid food systems (Maxwell, 1954; Carson *et al.*, 2006; Wang *et al.*, 2006): the Parallel model (parallel to electric current), the Maxwell-Eucken 1 (ME-1) (particles are in continuous liquid), the EMT model (Effective Medium Theory), the Maxwell-Eucken 2 (ME-2) (liquid is in continuous solid) and the Series model (perpendicular to electric current).

Assuming analogy between heat and electricity transfer, the principle and approach of these effective thermal conductivity modeling studies can be applied for modeling the effective electrical conductivity of particle-fluid food mixtures. The electrical conductivity prediction using these models is not complicated, thus useful in practical industrial applications. The structure of solid particles dispersed in continuous liquid, Maxwell-Eucken 1 (ME-1), is the most useful model that can be effectively used for electrical conductivity evaluation in ohmic heating processing of particle-fluid food systems. The Parallel and Series models may not exist in real food processing situations, but they can indicate the useful limit values of highest and lowest electrical conductivity of all two-phase structures. For ohmic heating processing of particle-fluid food systems, the electrical conductivity value can be evaluated using the Maxwell-Eucken 1 (ME-1) for solid particles dispersed in continuous liquid phase (Zhu *et al*, 2010):

$$\sigma = \frac{f_L \sigma_L + f_S \sigma_S \dfrac{3\sigma_L}{2\sigma_L + \sigma_S}}{f_L + f_S \dfrac{3\sigma_L}{2\sigma_L + \sigma_S}} \tag{2.11}$$

where σ is the effective electrical conductivity of the structure of a food mixture (S/m); f_L and f_S are volume fraction of liquid and particles (solid) respectively; σ_L and σ_S are electrical conductivity of the liquid and the solid phase respectively (S/m). For a food mixture of carrier fluid containing different types of solid particles, the electrical conductivity value can be evaluated using the unified model. The form of this model was developed by Brailsford and Major (1964) for determining the effective electrical conductivity of multi-component materials.

$$\sigma = \frac{\sum_{i=1}^{N} f_i \sigma_i \dfrac{d_i \tilde{\sigma}}{(d_i - 1)\tilde{\sigma} + \sigma_i}}{\sum_{i=1}^{N} f_i \dfrac{d_i \tilde{\sigma}}{(d_i - 1)\tilde{\sigma} + \sigma_i}} \tag{2.12}$$

where N is the number of material components; f_i is volume fraction of component i; σ_i is electrical conductivity of component i (S/m); $\tilde{\sigma}$ is electrical conductivity of the continuous phase

(S/m); d_i is shape/size factor (dimensionless). Wang *et al.* (2006) recommended $d_i = 3$ as the most common d_i value presented in the literature.

2.7.2 MODELING OF THE OHMIC HEATING PROCESS

Studies have been done to establish appropriate models to understand the complex ohmic heating process of liquids containing particulates either in a static heater or in a continuous unit (Sastry and Li, 1996). The temperature of the liquid and particles must be identified to determine the efficiency of the ohmic heating process like conventional aseptic processing of particulate low-acid foods. As mentioned, it is arduous to monitor the temperature of moving particles without interfering with the process; an alternative is to make use of modeling to predict the temperature. A full model describing the electric, thermal, and flow behaviors during continuous ohmic heating requires the simultaneous solution of the equations of Laplace, Fourier, and Navier-Stokes. Thermophysical and electrical properties (viscosity, electrical conductivity, specific heat, thermal conductivity, and density values) are needed as input data for the model.

Sastry and Palaniappan (1992c) suggested an iterative method to determine the time-temperature profile of the fluid and of the middle of particles during ohmic heating. Marcotte (1999) adapted the iterative procedure to establish time-temperature, velocity, and electric field distribution profiles within the fluid during ohmic heating both in space and time. Starting from an estimate of the initial temperature throughout the ohmic heating column, thermophysical and electrical properties are calculated. Secondly, the momentum and Laplace equations are solved to obtain the velocity and the electric field (voltage gradient) distribution at steady state. Thirdly, the heat generation is calculated and the energy balance equation is modeled. The continuous ohmic heating column is filled with the solution that remained still during the experiment and time/temperature profiles are recorded at time intervals and along the geometry of the ohmic heating column until it reached steady state. For the next time increment, the momentum, Laplace, and energy equations are solved and properties are calculated through an iterative adjustment until a convergence is reached for the solution at this specific time increment. Convergence is attained by adjusting the number of elements and the time step and certain parameters specific to the successive substitution solver.

The resulting partial differential equations are remarkably non-linear as a result of the temperature dependence of physical properties. Also, these equations contain parameters that are interrelated: electrical conductivities of particles and carrier fluids, residence time distribution of particles, thermal properties of particles, and rheological properties of fluids. Therefore, coupled electrical, momentum, and thermal equations should be solved numerically with commercial computational fluid dynamics (CFD) software, usually using the finite element method to obtain the temperature distribution. For handling complex geometry and a variety of boundary conditions, the finite element technique is preferred. The solver Fluent performs calculations involving laminar, transitional, and turbulent flows, various modes of heat transfer, chemical reaction, multiphase flows, and other complex phenomena.

For static thermal design, it is not necessary to model the flow explicitly, only the coupled electrical and thermal partial differential equations are solved to find the temperature distribution. de Alwis and Fryer (1990b) developed a model for ohmic heating of solid-liquid mixtures for a single particle in a static heater. Ye *et al*. (2004) used magnetic resonance imaging (MRI) temperature mapping to simulate and verify heating in a static heater. The thermal behavior of particles in a still liquid is harder to get. In this case, the conduction heat transfer equation and a temperature dependent internal energy generation govern the heat transfer for particles with a time dependent boundary condition at the surface of the particle and uniform initial conditions.

2.7.2.1 THERMAL BEHAVIOR

The Fourier thermal energy transfer balance is expressed as follows (Marcotte, 1999):

$$\rho_f C_{pf}\left(\frac{\partial T}{\partial t}+\nu\cdot\nabla T\right) = \nabla\cdot\left(k_f\,\nabla T\right) + q^{"} - p\nabla\cdot\nu - \nabla\cdot q_r + \Psi - q_p \qquad (2.13)$$

The first term ($\nabla\cdot(k_f\,\nabla T)$) of equation (2.13) on the right-hand side represents the heat transferred by conduction through the fluid, the second term (q") is the energy generation rate, negligible in conventional thermal processing but very important in ohmic and microwave heating. The third term ($p\nabla\cdot\nu$) represents the work done by the fluid on its surroundings, usually zero in the case of an incompressible fluid. The fourth term ($\nabla \cdot q_r$) is the radiative heat transfer, negligible for food fluids under these conditions. The fifth term (Ψ) is the viscous dissipation, significant in scraped surface heat exchangers but negligible in holding tube or ohmic heaters. The sixth term (q_p) is the energy transferred to the particles in suspension. In the case where only the liquid is ohmically processed this term would be zero. This leads to the reduced form of equation (2.13) for liquid temperature profile (Marcotte, 1999):

$$\rho_f C_{pf} \left(v \cdot \nabla T\right) = \nabla \cdot \left(k_f \nabla T\right) + q'' \tag{2.14}$$

For a pilot plant scale APV-type ohmic heater column, an axi-symmetric problem in cylindrical coordinates can be assumed. Only the radial and axial directions are important. The fluid is assumed to possess a convective velocity, v, in the z-direction only. Negligible radial convective velocity variations are assumed. At steady state, there is no variation of temperature with time for a particular position. There are no heat losses to the surroundings. The conduction in axial direction can be neglected because the term is small as compared to the axial convection. This leads to the particular form of equation (2.14) (Marcotte, 1999):

$$\rho_f C_{pf}\, v_z \frac{\partial T}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\, k_f \frac{\partial T}{\partial r}\right) + \dot{Q}_f \tag{2.15}$$

In the case where the liquid and particles are ohmically processed, the conduction heat transfer equation and a temperature dependent internal energy generation govern heat transfer for particles. Equations (2.16-2.19) are used to solve for the temperature profile. The energy transfer to the particles (q_p) from equation (2.13) is not zero and is given by (Marcotte, 1999):

$$q_p = \sum_i \left(h_{fpi}\, A_i / V_i\right)\left(T_{bf} - T_{spi}\right) \tag{2.16}$$

For each ith particle, the value of the surface temperature, area and convective heat transfer coefficient would be different and it should be determined by the solution of the conduction heat transfer equation (Marcotte, 1999):

$$\nabla \cdot \left(k_{pi}\, \nabla T_{pi}\right) = \rho_{pi} \mathrm{C}_{ppi} \frac{\partial T}{\partial t} + q_p \tag{2.17}$$

The conduction heat transfer equation for each particle is subject to the following surface condition (Marcotte, 1999):

$$k_{pi}\, \nabla T_{pi} \cdot \vec{\mathrm{n}} = h_{fpi} \left(T_{spi} - T_{bf}\right) \tag{2.18}$$

Finally, two boundary conditions can be applied. First, the wall boundary condition is expressed (Marcotte, 1999):

$$U_w \left(T_{bf} - T_{sw}\right) = k_f\, \nabla T_f \cdot \vec{\mathrm{n}} \tag{2.19}$$

U_w is the overall heat transfer coefficient to the surroundings, incorporating convective and wall conductive resistances and can be assumed to be 0 if the walls are insulated. The second boundary condition is axial symmetry with temperature at the inlet (Marcotte, 1999):

$$T\,|_{\,z=0} = T_i \tag{2.20}$$

Constant gradient of temperature in the z-direction and steady state are assumed. The initial condition usually assumes the same uniform temperature everywhere: $T_p = T_f = T_i$ at $t = 0$. To solve this equation, the velocity fields are essential and can only be deduced from the simultaneous solution of the momentum transfer problem. In the case that a particle-liquid mixture is processed, the process of solving these equations is even more arduous since the surface particle temperature must be found. This necessitates the solution of the conduction heat transfer equation for each single particle. The fluid-to-particle interfacial heat transfer coefficient should also be utilized. To simply the process, relevant assumptions in solving the partial differential equations are often made such as constant thermal properties, homogeneous and isotropic particle, pure conduction heating within the particle and no phase change in the fluid and particle during processing (Marcotte, 1999).

2.7.2.2 ELECTRIC FIELD DISTRIBUTION

To find the heat generation rate, it is necessary to first solve the Laplace equation for the electric field distribution in the whole fluid at steady state (Marcotte, 1999):

$$\nabla \cdot \left(\sigma_f \nabla V\right) = 0 \tag{2.21}$$

The electrical conductivity is temperature dependent. The value of σ_f increases with temperature as in equation (2.3). Therefore, the solution of the Laplace equation is dependent on the temperature distribution in the spacing tube. In cylindrical coordinates, the electric field distribution of the spacing tube between two electrodes can be calculated by (Marcotte, 1999):

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\sigma_f\,\frac{\partial V}{\partial r}\right)+\frac{\partial}{\partial z}\left(\sigma_f\,\frac{\partial V}{\partial z}\right) = 0 \tag{2.22}$$

The general volume based heat generation rate is given by (Marcotte, 1999):

$$\dot{Q}_f = \sigma_f\left(\nabla V \cdot \nabla V\right) = |\nabla V|^2\,\sigma_f \tag{2.23}$$

In cylindrical coordinates, the volumetric heat generation term is (Marcotte, 1999):

$$\dot{Q}_f = \sigma_f\left(\left(\frac{\partial V}{\partial r}\right)^2+\left(\frac{\partial V}{\partial z}\right)^2\right) \tag{2.24}$$

The following boundary conditions can be applied: axial symmetry, electrically insulated wall, and top and bottom electrodes at fixed potential (Marcotte, 1999).

2.7.2.3 FLOW BEHAVIOR

The general equation for fluid flow or Navier-Stokes (Bird *et al.*, 1960) is used with only the z-component of the motion. Considering a collinear system i.e. a vertical cylindrical column in which electrodes are inserted, the momentum equation for the vertical velocity *v* in cylindrical coordinates (Burmeister, 1983) is expressed by:

$$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+v_z\frac{\partial v_z}{\partial z}\right) = -\frac{\partial p}{\partial z}+\rho g_z+\frac{1}{r}\frac{\partial}{\partial r}\left(\eta_a\, r\frac{\partial v_z}{\partial r}\right)+\frac{\partial}{\partial z}\left(\eta_a\frac{\partial v_z}{\partial z}\right) \qquad (2.25)$$

Again, the azimuthal, θ, direction component is assumed negligible. Radial velocities (v_r) in the system are two orders of magnitude smaller than the axial velocities (Muller *et al.,* 1994); therefore viscous dissipation due to radial velocities can be neglected. In this equation, a natural convection (free convection) term arises from the temperature difference between the wall and the centre of the tube (ρg_z) resulting from changes in density. Using the Boussinesq approximation, it is possible to express changes in density by changes in temperature, considering a coefficient of expansion (Marcotte, 1999):

$$\rho = \rho_0\left[1+\beta\,(T-T_0)\right] \qquad (2.26)$$

The flow velocity in the radial direction (v_r) is zero. A small term of Boussinesq equation can be omitted. The resulting simplified equation is obtained (Marcotte, 1999):

$$\rho\frac{\partial v_z}{\partial t}+\rho v_z\frac{\partial v_z}{\partial z} = -\frac{\partial p}{\partial z}+g\rho_0\,\beta(T-T_0)+\frac{1}{r}\frac{\partial}{\partial r}\left(\eta_a\, r\frac{\partial v_z}{\partial r}\right) \qquad (2.27)$$

The velocity in the z-direction is a function of the radial position and is determined by the flow regime. Marcotte (1999) suggested using a laminar flow residence time as a conservative practice. Assuming a fully developed flow at the inlet, the velocity for a Newtonian fluid fully developed flow can be found from the following equation at any radial position:

$$v_z\,(0,r) = \frac{2\dot{v}}{\pi R^2}\left[1-\left(\frac{r}{R}\right)^2\right] \qquad (2.28)$$

Where $\dot{v}$ is the volumetric flow rate (m^3/s).

CHAPTER 3

ELECTRICAL CONDUCTIVITIES OF CABBAGE AND DAIKON RADISH

3.1 ABSTRACT

Ohmic heating was applied to cabbage and daikon radish for ohmic heating behavior of two-phase aqueous food systems. Shredded cabbage (50% v/v) and daikon radishes cubes (57% v/v) and different salt solutions (0.15, 0.5, 1, 1.5, and 1.85%) were poured into a Teflon-coated static ohmic heating cell and heated at different constant voltages of 65, 80, 100, 120, and 135 V. The samples were heated from 30 to 70°C using low and high frequency alternating current of 60, 2070, 5030, 7990, and 10000 Hz. Voltage, current, time, and temperature were logged at selected intervals and used to calculate electrical conductivities as a function of temperature. For the modeling part, 750 g of a blended crude puree (particle size < 0.5 mm) was used to densely fill the ohmic heating cell. Of the two vegetables examined, daikon radish gave the highest value for electrical conductivity at 1.07 S/m at 30°C and 1.85%, 100 V, and 5030 Hz while cabbage gave a value of 0.81 S/m under the same experimental conditions. The general trend for cabbage was that the magnitude of the electrical conductivity increased with increasing frequency at high voltage, but decreased at low voltage. An opposite trend was observed for daikon radish. Electrical conductivities were found to increase quadratically with temperature in all cases. Electrical conductivities were higher as the salt concentration and the voltage were increased for both vegetables. A slight slope change was observed in all cases between 50 and 60°C possibly due to heat induced structural changes. The response surface models revealed that linear, cross products, as well as quadratic effects were significant with R^2 over 0.976. The first Maxwell-Eucken model, which describes solid particles dispersed in continuous liquid, showed good agreement between predicted electrical conductivity values and experimental data. This model provided a useful and relatively simple new approach to predict the effective electrical conductivity for two-phase food systems of solid food particles immersed in liquid food.

3.2 INTRODUCTION

Ohmic heating is an advanced food processing method where an electrical current is passed through an electrically conducting food product for rapid heat generation. Most foods contain ionic species such as salts and acids, hence, electric current can be made to pass through the food and generate heat inside it (Palaniappan and Sastry, 1991a). The ohmic heating concept is not new and was used in the 19th century to pasteurize milk. The ohmic heating process was originally developed by the United Kingdom Electricity Research and Development Centre and was licensed to APV Baker Ltd for commercial exploitation of the results in 1983 (Skudder, 1992). Apparently due to the lack of inert materials for the electrodes this technology was later abandoned. Ohmic heating technology recently has gained new attention because the products processed are of clearly higher quality than those obtained by conventional techniques. The electrical conductivity of food components is the key property in this process as it controls the ohmic heating rate. Ohmic heating preservation can be a real alternative to conventional heat processing of food reducing treatment time and improving quality food products (Kim *et al.*, 1996; Castro *et al.*, 2003).

Heat is generated volumetrically and the product does not experience a large temperature gradient within itself, even when particulates are present. The electrical energy provided by the power supply, is transformed into thermal energy. Under certain conditions, it is even possible to heat the centre of the particle faster than the liquid (Fryer and de Alwis, 1989; Sastry and Palaniappan, 1992a). The amount of heat generated is directly related to the current induced by the voltage gradient in the field and the electrical conductivity (Sastry and Li, 1996). The applicability of ohmic heating depends on the product electrical conductivity, which is a function of the structure of the material and often changes by heating. Ohmic heating is based on a food's ability to conduct electrons from one electrode to another. In practice, most vegetable solid particles have lower conductivities than liquids. Increased electrolyte content within solid foodstuffs, and thus increased electrical conductivity, can be achieved by salt diffusion (Wang and Sastry, 1993). 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 main mechanism claimed in these studies to explain the firming effect of low temperature low time (LTLT) pre-treatment is the demethoxylation of pectic materials of the cell wall catalysed by the pectin methylesterase. Pre-treatment in salted water could thus present a double advantage in the case of ohmic heating, by increasing the electrical conductivity and improving the final textural quality of the product after processing.

Zareifard *et al.* (2003) looked at the effects of particle concentration, size, and location on electrical conductivity and heating behavior during the ohmic heating of two-phase food systems. Wang and Sastry (1993) demonstrated that salt infusion could increase the electrolytic content within foodstuffs and therefore raise electrical conductivity. This infusion may be achieved by a slow soaking process or a more rapid blanching process in salt solution. Wang and Sastry (1993) were able to determine salt diffusivity in vegetable tissues. Sarang and Sastry (2007) looked at the effects of salt concentration and temperature on the diffusion and equilibrium distribution coefficients of salt within vegetable tissue. Even though the electric field strength can be exactly monitored, the behavior of plant tissue electrical conductivity is very complicated, and relies upon on multiple factors, such as frequency, temperature, and the electro-thermal damage kinetics of the tissue cell membranes (Lebovka *et al.* 2007b; Kulshrestha and Sastry, 2006). Most often a boost in the alternating electric field frequency is required to underrate unacceptable electrochemical reactions between electrodes and food product (Samaranayake and Sastry, 2005). Such a growth causes a tissue electrical impedance decrease. In addition, electroporation process of plant tissue cell membranes was stated to be more marked at low frequencies (De Vito *et al.*, 2008; Kulshrestha and Sastry, 2003). Moreover, food product temperature rise affects both electrical conductivity and electroporation rate, and at temperatures above 50°C, thermal plasmolysis can be observed (Wang and Sastry 1997; Lebovka *et al.*, 2007a). Besides, membrane break comes along a meaningful increase of the tissue electrical conductivity and may affect the process of ohmic heating (Sarang *et al.*, 2007; Lebovka *et al.*, 2007a and b). The time of thermal impact necessary to attain a high level of damage relies upon the temperature and varies by individual differences in fruit and vegetables. Frequency dependency of the electrical conductivity of plant tissue can be explained by electrical properties of a cell membrane, which can be represented as a resistor and capacitor. Increased permeability or mobility of molecules caused by the applied electric field increases tissue electrical conductivity. It is possible that at lower frequency, the longer polarity change cycle provides sufficient time to induce enough membrane potential to cause electro-permeabilization effects.

Many studies have been conducted on modelling electrical conductivity in a multiphase food system (de Alwis and Fryer, 1992; Sastry and Palaniappan, 1992a; Ye *et al.*, 2004; Carson *et al.*, 2006). Nevertheless all developed models contain harsh mathematical or numerical computations and include numerous parameters that were hard to obtain experimentally. Hence the previous models are complicated and not useful in practical applications. To overcome this, in 2010, Zhu *et al.* looked over and compared different theoretical models for the solid-liquid food mixtures based on the experimental data. Taking into account that an analogy can be made between heat and electricity transfer, five existing thermal conductivity theoretical models (series, parallel, two forms of Maxwell-Eucken models and effective medium theory) were used to determine the effective electrical conductivity of various solid-fluid structural systems. They concluded that Parallel and Series models are not practically applicable in real food system; however, they can indicate the useful limit values of highest and lowest electrical conductivity among two-phase structures. The first Maxwell-Eucken model, which describes solid particles dispersed in continuous liquid, illustrated the best concordance between predicted electrical conductivity values and experimental data. This model provided a useful and relatively simple new approach to predict the effective electrical conductivity for mixtures of different types of solid food particles immersed in liquid food. Studies on system parameters and overall electrical conductivity properties of two-phase foods are limited. Knowledge of the electrical conductivity values of the multi-phase food system as a whole and those of its components is essential in designing a successful ohmic heating process.

The objectives of this study were as follows:

a) to gather data for a better understanding of electrical conductivity of cabbage and daikon radish and its influencing system parameters (individual effects, interactions);

b) to make an analogy between heat and electricity for calculating the effective electrical conductivity of particle-fluid mixtures with the Maxwell-Eucken-1 model of solid particles dispersed in a continuous liquid phase.

3.3 MATERIALS AND METHODS

3.3.1 EXPERIMENTAL SET-UP

A diagram of the static ohmic heating cell unit system is illustrated in Figure 3.1 This system consisted of a cylindrical Teflon cell with a length of 280 mm, an internal diameter of 70 mm, and walls 33 mm thick, and two titanium electrodes spaced 190 mm apart. This system was connected to a Behlman PID power control unit and a Bectrol data logger, with several insulated thermocouples and Vijeo Citect Runtime Version 7.0r3 control software. Voltage and alternating current were supplied and controlled by a power unit that comprised a variable transformer, an isolation transformer, a voltage transducer, a current transducer, power relays, and fuses. Four rigid Teflon-insulated thermocouples (Intempco) were mounted along the cell; two of these thermocouples were positioned close to the electrodes, while the two others were positioned at ¼ of the distance between them. The tips of these thermocouples were located at the symmetric axis of the ohmic heating cell. Other thin flexible thermocouples Teflon-coated, K-type, (Omega Engineering) were installed through the air cap at the centre of the cell and thus measure the temperature of the liquid medium or the solid particles.

Thermal lags due to Teflon coating of thermocouples were corrected using data from preliminary calibration experiments involving comparison with a certified mercury-in-glass thermometer (National Research Council, NRC # 1598, Canada) and uncoated thermocouple junctions under conventional heating conditions. At the beginning of each experiment, particles were fouled into the cell in order to have shredded cabbage (50% v/v) and daikon radishes cubes (57% v/v) and carrier fluid (0.15, 0.5, 1, 1.5, and 1.85% salt water) was poured on the air cap to fill the empty space of the ohmic heating cell. The sample was heated from 30 to 70°C using an alternating current of 60, 2070, 5030, 7990, and 10000 Hz at different constant voltages of 65, 80, 100, 120, and 135 V. The temperatures as well as the voltage and current of AC power were recorded every 5 s using the data logger. For each experiment, values of voltage and current were used to calculate the electrical conductivity which was plotted against the temperature. All experiments were performed in duplicates.

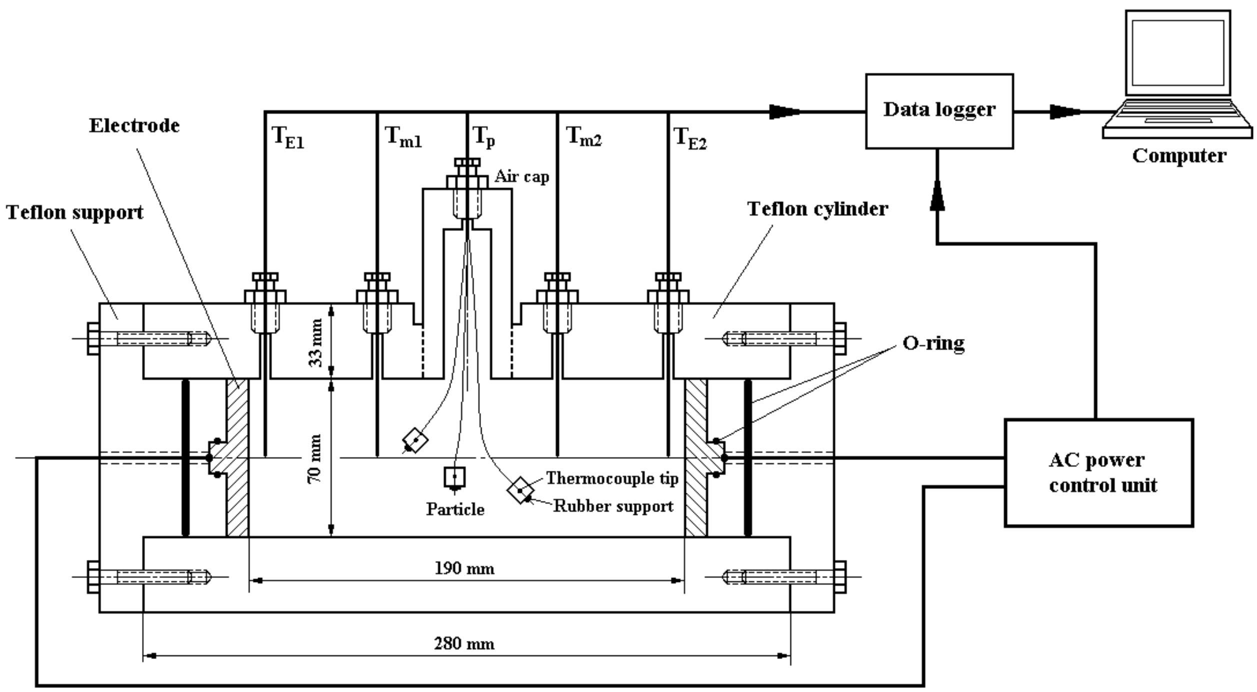


Figure 3.1. Schematic of the ohmic heating experimental system

3.3.2 SAMPLE PREPARATION

Three types of formulations were used in the experimental study: blended solids, carrier fluid, and solid food particles in carrier fluid (Table 3.1). Fresh vegetables (cabbage and daikon radish, or white radish) were purchased from a local supplier (Loblaws, St-Hyacinthe, QC, Canada). Daikon radishes were manually cut into irregular particles with a volume similar to a 1-cm cube while cabbage was shredded in irregular thin pieces about (2 x 5 x 80) mm^3. Vegetables were peeled before cutting.

Two-phase food systems were tested using carrier fluid with various solid phase conditions (Table 3.1). Particles were placed in the cell in order to have shredded cabbage (50% v/v) or daikon radish cubes (57% v/v) and carrier fluid containing different salt concentrations (0.15 - 1.85%) were poured to fill the empty space of the ohmic heating cell. Four cubic particles (with one thin flexible thermocouple installed at the center of each particle) were prepared to monitor the temperature profiles of the solid phase during the process. The temperatures were monitored

Table 3.1. Samples of food systems prepared for ohmic heating experiments

Materials tested	**Salt concentration**	**Particle concentration**	**Particle size**
	(%, w/w)	**(%, v/v)**	
Blended solids		100 (daikon radish)	Crude puree (< 0.5 cm)
Carrier fluid	0.15, 0.5, 1.0, 1.5, 1.85		
Particles in carrier fluid	0.15, 0.5, 1.0, 1.5, 1.85	57 (daikon radish)	1-cm cube
	0.15, 0.5, 1.0, 1.5, 1.85	50 (cabbage)	Shredded ± (2 x 5 x 80) mm^3

before the experiment started in order to obtain uniform initial temperature conditions. In order to calculate the electrical conductivity, an assumption was made for shredded cabbage. In this case, many authors have pointed out that the solid particles heat up more rapidly than the liquid (Sastry and Palaniappan 1992a; Zareifard *et al.*, 2003). This way fluids with suspended particles could be treated as liquids in ohmic heating in which only the temperature of the liquid is controlled (Larkin and Spinak, 1996). Therefore, we considered both, solid and liquid phases, as a single phase. On the other hand, for the 1-cm daikon radish cubes, no such assumption was made and a volumetrically integration was used to measure the effective temperature of the static ohmic unit cell based on the mean temperature of the liquid and the particles.

For the electrical conductivity model part, daikon radishes were blended (about 400 g per batch for 3 min) using a domestic blender (UK100, Braun, Kronberg, Germany) to make a crude puree (particle size < 0.5 mm). About 750 g of the crude puree was used to densely fill the ohmic heating cell for each test. Test purees used were prepared on the same day.

3.3.3 ELECTRICAL CONDUCTIVITY

Electrical conductivity (σ, S/m) is the relationship between the geometry of the cell and the resistance of the sample as expressed by Equation (3.1) (Sastry and Palaniappan, 1992a):

$$\sigma = \frac{L}{AR} = \frac{L\,I}{A\,U} \qquad (3.1)$$

where L is the gap between two electrodes (m); A is the cross-section area in the heating cell (m^2); R is the electrical resistance of the sample (Ω); I is current (A); U is voltage (V).

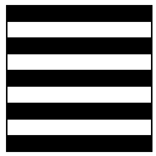
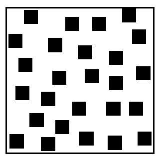
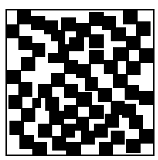
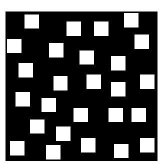
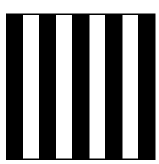
3.3.4 ELECTRICAL CONDUCTIVITY MODEL DEVELOPMENT

Assuming an analogy between thermal conductivity and electrical conductivity, five existing thermal conductivity theoretical models (series, parallel, two forms of Maxwell–Eucken models and effective medium theory) can be applied and evaluated for electrical conductivity of various solid-fluid structural systems (Table 3.2). These models apply for the ohmic heating process of homogenous particle-fluid foods. For the ohmic heating process of particle-fluid foods, the most common case is heterogeneous food matrix with higher liquid fraction than solid, where the solid particles are dispersed in continuous liquid phase. Equation 3.7, developed by Brailsford and Major (1964) for a multiphasic system, can be used to determine various dispersion models:

$$\sigma = \frac{\sum_{i=1}^{N} f_i \sigma_i \dfrac{d_i \tilde{\sigma}}{(d_i - 1)\tilde{\sigma} + \sigma_i}}{\sum_{i=1}^{N} f_i \dfrac{d_i \tilde{\sigma}}{(d_i - 1)\tilde{\sigma} + \sigma_i}} \qquad (3.7)$$

where N is the number of material components; f_i is volume fraction of component i; σ_i is electrical conductivity of component i (S/m); d_i is shape/size factor (dimensionless); $\tilde{\sigma}$ is electric conductivity of the continuous phase (S/m).

Table 3.2. Effective electric conductivity models of five basic structures of two-component (solid-liquid) systems (Zhu *et al.*, 2010).

Model name	Structure schematic	d_i and $\tilde{\sigma}$ values	Model equation and number*	
Parallel model (parallel to electric current)		$d_i \to \infty$ or $\tilde{\sigma} = \sigma_i$	$\sigma = f_L \sigma_L + f_S \sigma_S$	(3.2)
Maxwell-Eucken 1 (ME-1) model (particles are in continuous liquid)		$d_i = 3$ and $\tilde{\sigma} = \sigma_L$	$\sigma = \dfrac{f_L \sigma_L + f_S \sigma_S \dfrac{3\sigma_L}{2\sigma_L + \sigma_S}}{f_L + f_S \dfrac{3\sigma_L}{2\sigma_L + \sigma_S}}$	(3.3)
EMT model (Effective Medium Theory)		$d_i = 3$ and $\tilde{\sigma} = \sigma$	$f_L \dfrac{\sigma_L - \sigma}{\sigma_L + 2\sigma} + f_S \dfrac{\sigma_S - \sigma}{\sigma_S + 2\sigma} = 0$	(3.4)
Maxwell-Eucken 2 (ME-2) model (liquid is in continuous solid)		$d_i = 3$ and $\tilde{\sigma} = \sigma_S$	$\sigma = \dfrac{f_L \sigma_L \dfrac{3\sigma_S}{\sigma_L + 2\sigma_S} + f_S \sigma_S}{f_L \dfrac{3\sigma_S}{\sigma_L + 2\sigma_S} + f_S}$	(3.5)
Series model (perpendicular to electric current)		$d_i = 1$ or $\tilde{\sigma} \to 0$	$\sigma = \dfrac{1}{f_L / \sigma_L + f_S / \sigma_S}$	(3.6)

*where σ is the effective electric conductivity of the structure of a food mixture (S/m); f_L and f_S are the volume fraction of liquid and particles (solid), respectively; σ_L and σ_S are electric conductivity of the liquid and the solid phase, respectively (S/m); d_i is shape/size factor (dimensionless); $\tilde{\sigma}$ is electric conductivity of the continuous component (S/m).

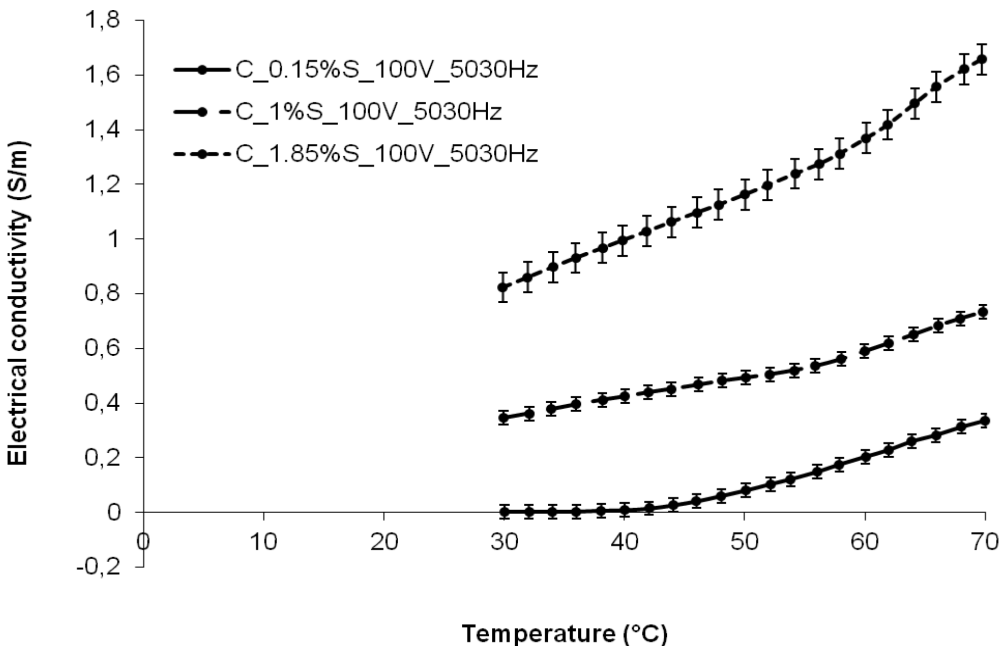
Previous authors have discussed the importance of the size of the particles in ohmic heating and recommended a value of 3 for d_i (Zareifard *et al.*, 2003; Wang *et al.*, 2006). Taking equation (3.7) for liquids and solids particles, gives us five different dispersion models (Table 3.2): parallel dispersion $d_i \rightarrow \propto$ and $\tilde{\sigma} = \sigma_i$, serial dispersion $d_i = 1$ or $\tilde{\sigma} \rightarrow 0$, and dispersions according to Maxwell-Eucken equations ME-l and ME-2 $d_i = 3$ and $\tilde{\sigma} =$ electrical conductivity of the continuous phase, which is liquid in ME-l and solid in ME-2 (Maxwell, 1954). The model for dispersion of particles in a liquid (ME-1) best represents our own experiments and will be used to calculate the effective electrical conductivity of the two-phase food system.

3.4 RESULTS AND DISCUSSION

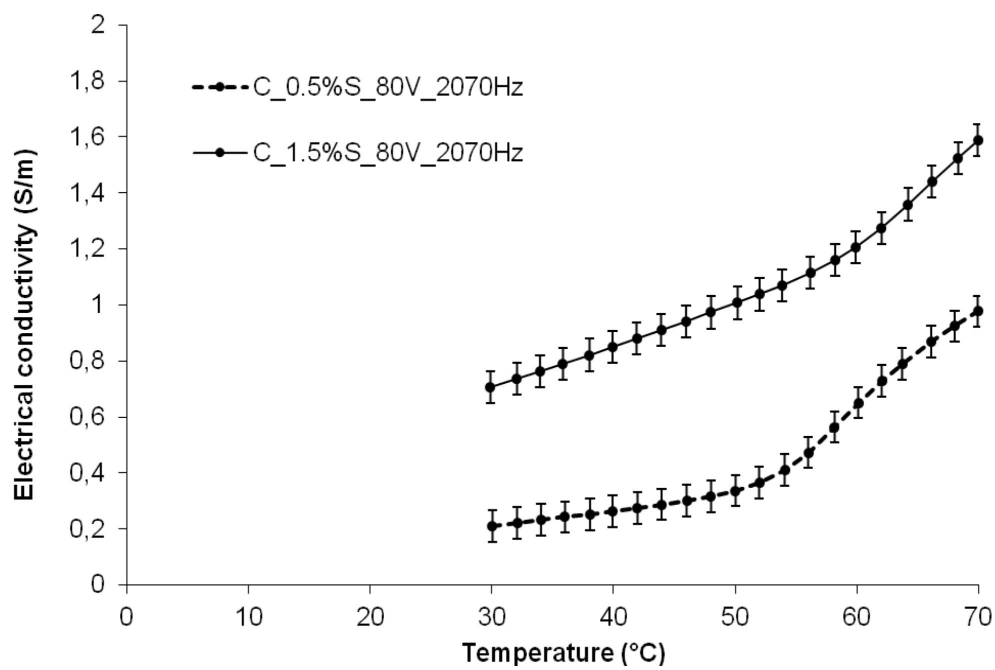
3.4.1 ELECTRICAL CONDUCTIVITY AS AFFECTED BY SALT CONCENTRATION

Figure 3.2 shows salt concentration and temperature effects on electrical conductivities of two-phase food systems. Each experimental condition was done in two replicates. A broad range of electrical conductivities were for salt concentration varying from 0.15 to 1.85% and temperature from 30 to 70°C : (a) from 0.01 to 0.36 S/m at 30 to 70°C and 0.15%, from 0.37 to 0.70 S/m at 30 to 70°C, and 1%, and from 0.80 to 1.65 S/m at 30 to 70°C and 1.85%; (b) from 0.20 to 0.95 S/m at 30 to 70°C and 0.5%, and from 0.70 to 1.60 S/m at 30 to 70°C and 1.5%.

The general trend was that the magnitude of the electrical conductivity increased with temperature and salt concentration. Electrical conductivities were found to increase quadratically with temperature in all cases. In fact, when the temperature was less than about 55°C, the increase in electrical conductivity was linear for each test material with temperature rise, while above that temperature, a slope change was observed, and the increases were more sharp (as shown in below figures). This is probably due to the fact that the vegetable materials were not blanched before the ohmic treatment and to the fact that the membrane perhaps broke at that point demonstrating that the low and high pasteurization treatment may be possible. It can be observed that the slope change is more radical for daikon radish as less initial damage was done to the vegetable; whereas, for shredded cabbage, the damage was initially done by shredding it all over.



a) Cabbage solutions



b) Daikon radish solutions

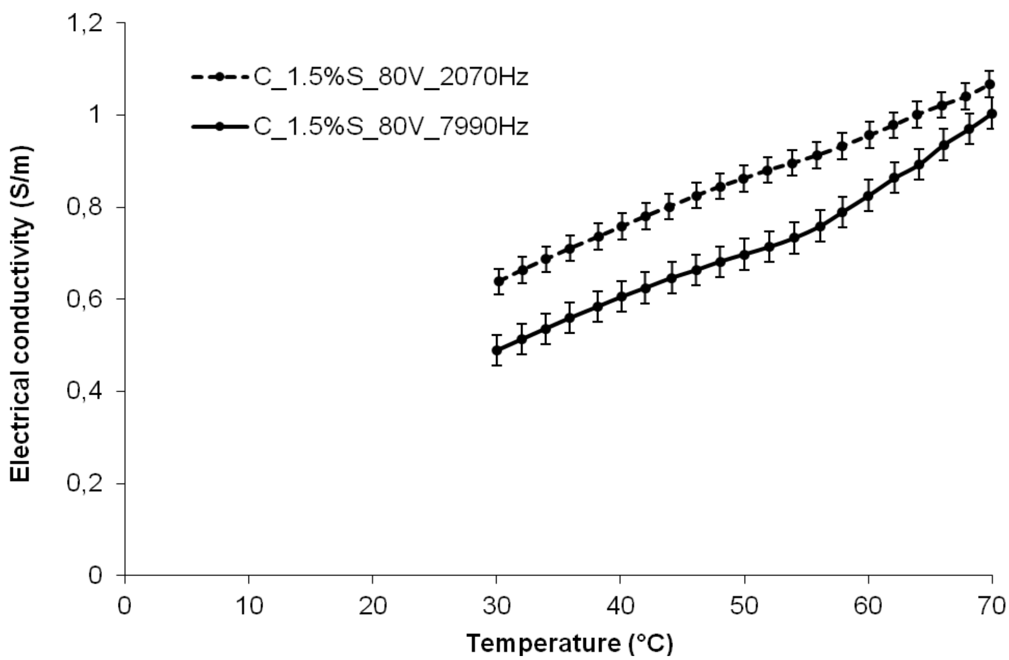
Figure 3.2. Salt concentration effect in electrical conductivities of two-phase food systems; a) Cabbage solutions, b) Daikon radish solutions

Yongsawatdigul *et al.* (1995) reported a synergy among salt and water content. Besides, the quadratic relationship between electrical conductivity and temperature at different salt content, there was a symbolic interplay amidst the salt content and the temperature. This observation goes along with the present study. In the current study, a quadratic effect for salt was observed when concentrations varied from 0.15 to 1.85% whereas in the case of Yongsawatdigul *et al.* (1995) the salt concentration varied over a broader range from 1 to 4%. Electrical conductivity growth during heating of biological tissues occur because of the increase in the ionic mobility caused by structural changes in the tissue like cell wall protopectin breakdown, expulsion of non conductive gas bubbles, softening, and lowering in aqueous phase viscosity (Sasson and Monselise, 1977). 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 and Sastry, 1997). Thus heating causes the mobility of moisture increase thereby, increasing ionic mobility, which in turn increases the electrical conductivity (Sarang *et al.*, 2007). 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.

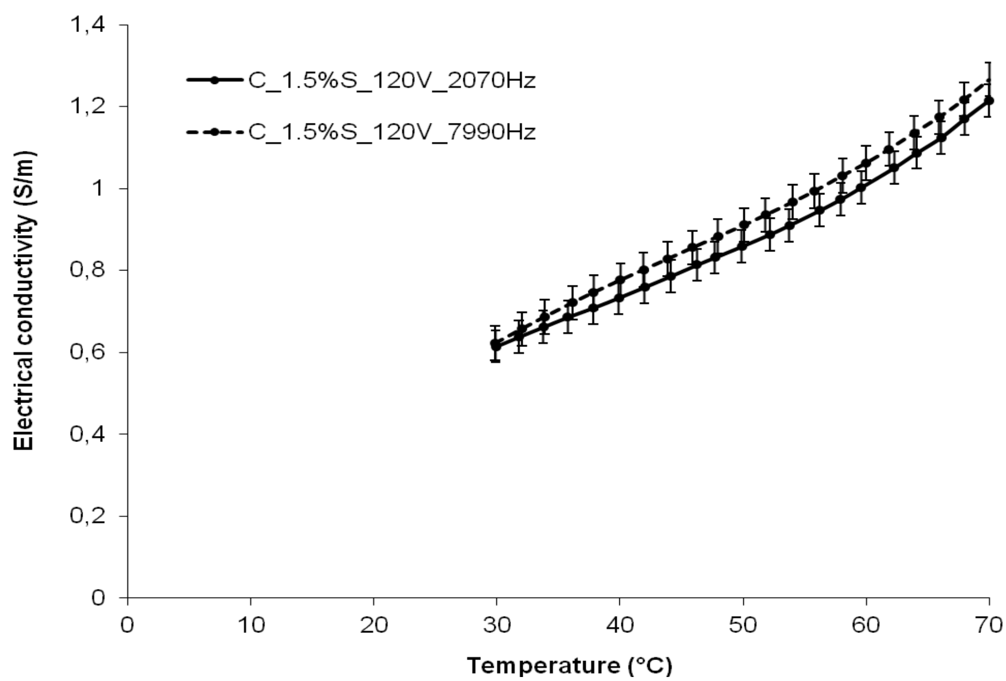
Sarang *et al.* (2008) found that higher electrical conductivity of peach and strawberry can be connected to their smoother tissues and so higher ionic mobility as to the harder tissues of apples, pineapple and pear. In addition, presence of abundant quantity of air may lead to lower electrical conductivity of apple tissues. Another determinant aspect determining the conductivity is the total ionic content of these biological tissues. Mavroudis *et al.* (2004) calculated porosity of fresh apples and found results as high as 20%. The presence of large amount of air might give a reason for low conductivity of apple tissues. Ohmic heat treatment of apples and potatoes allows a high level of membrane destruction and mechanical softening of tissues even at a moderate temperature of 50°C (Praporscic *et al.*, 2006). Their results show that tissue disintegration depends on several treatment parameters (field intensity, temperature, and time duration) and type of plant tissue. The potato tissue is more sensitive to the electrical treatment than the apple tissue is, and the rise of the sample temperature and damage degree was more pronounced for potatoes at the same field intensity. This can be related to a difference in the structural and electro-physical properties of potato and apple tissues. Note that the electrical conductivity of the undamaged apple tissue is lower than that of the potato. Apples have a high content of trapped air inside and potato is texturally stronger, since it has a high starch content, which preserves the skeleton of cells (Kaur *et al.*, 2002). No significant textural differences were found between samples treated at 40 or 50°C and fresh samples, but the firmness of samples cooked above 60°C decreased for high temperature/short time sterilisation of cauliflower florets by batch ohmic heating. Sensoy and Sastry (2004b) observed that mushrooms shrank and lost porosity. They notice that differences in particle type include variations not only in size and shape, but also tissue diffusivity differences. Liu (1992), Drusas and Vagenas (1988), and Wang and Sastry (1993) measured salt diffusivity in vegetable tissues. They showed that over the temperature range 50 to 70°C, serious changes occured in the potato tissue because of denaturation of the cell membrane and gelatinization of the starch granules, with the resultant destruction of the cell walls. Alike changes in potato above 70°C are achieved within an extremely rapid term (Liu, 1992).

3.4.2 ELECTRICAL CONDUCTIVITY AS AFFECTED BY FREQUENCY

Figure 3.3 shows frequency and temperature effects on electrical conductivities of two-phase food systems. Again, each experimental condition was done in two replicates. A broad range of electrical conductivities were found for frequencies ranging from 60 to 10000 Hz and temperature from 30 to 70°C: a) values varied from 0.65 to 1.10 S/m and from 0.50 to 0.95 S/m for 2070 Hz and 79890 Hz, respectively, over the range of processed temperature of 30 to 70°C; b) values varied from 0.60 to 1.20 S/m and from 0.62 to 1.25 S/m for 2070 Hz and 7990 Hz, respectively, over the range of processed temperature of 30 to 70°C; c) values varied from 0.68 to 1.57 S/m and from 0.83 to 1.82 S/m for 2070 Hz and 7990 Hz, respectively, over the range of processed temperature of 30 to 70°C; d) values varied from 0.93 to 1.89 S/m and from 0.95 to 1.87 S/m for 2070 Hz and 7990 Hz, respectively, over the range of processed temperature of 30 to 70°C. The general trend for cabbage solutions was that the magnitude of the electrical conductivity increased with increasing frequency at high voltage, but decreases at low voltage. On the other hand, for daikon radish solutions, it increased at low voltage, but remained constant at higher voltage. Electrical conductivities were found to increase quadratically with temperature in all cases and to be dependent of the frequency.

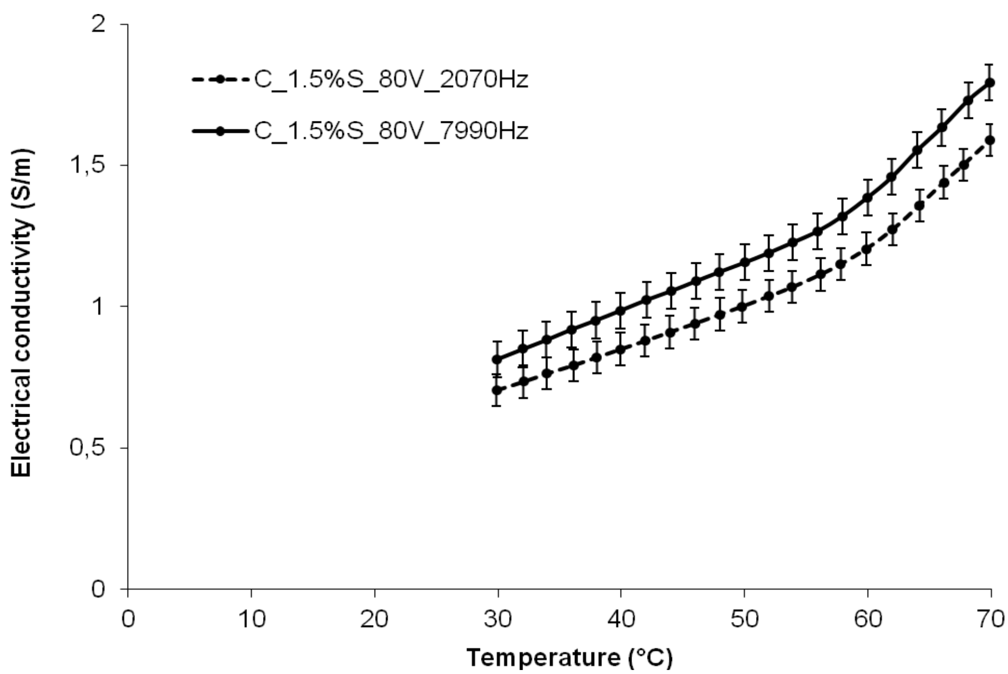


a) Cabbage solutions at low voltage

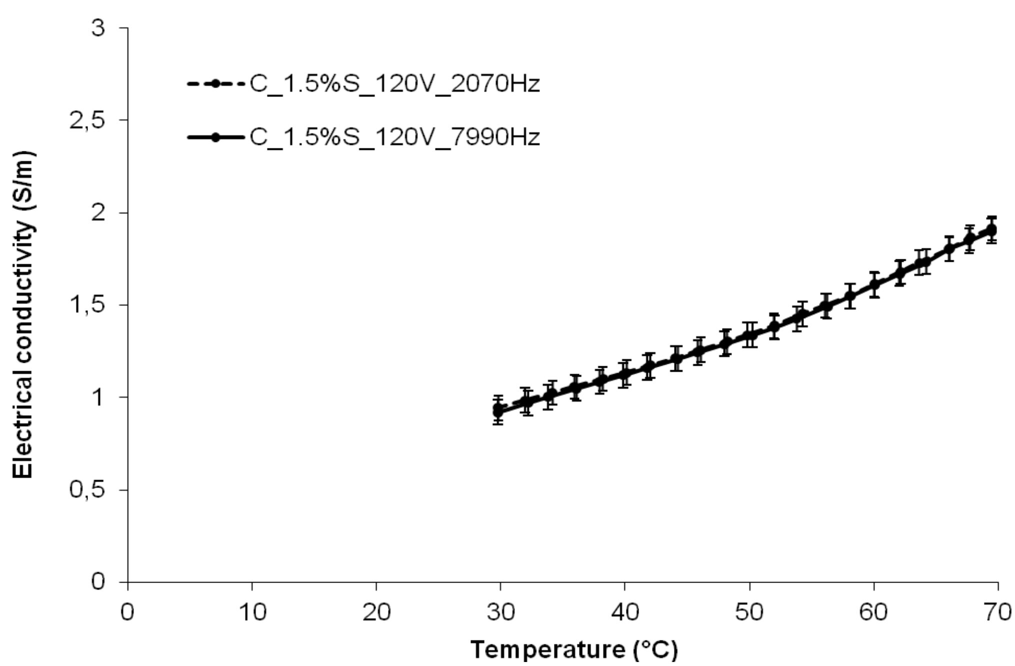


b) Cabbage solutions at high voltage

Figure 3.3. Frequency effect in electrical conductivities of two-phase food systems; a) Cabbage solutions at low voltage, b) Cabbage solutions at high voltage



c) Daikon radish solutions at low voltage



d) Daikon radish solutions at high voltage

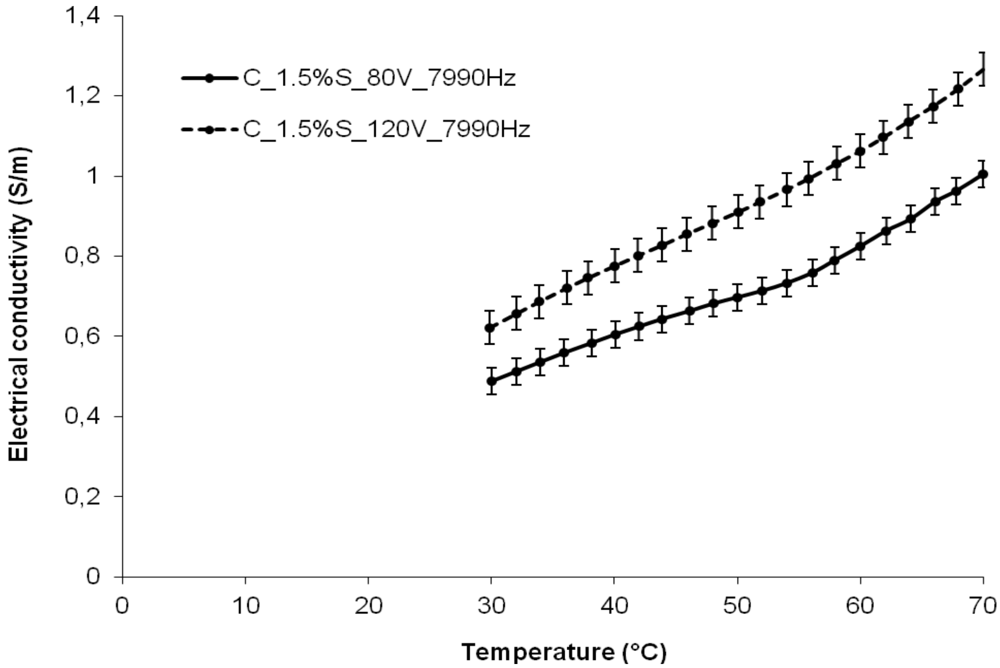
Figure 3.3. Frequency effect in electrical conductivities of two-phase food systems; c) Daikon radish solutions at low voltage, d) Daikon radish solutions at high voltage

Lima and Sastry (1999) studied the effects of frequency of alternating current on the alteration of heat and mass transfer properties. 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 the process. 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-treatments at this frequency require considerably less time than pre-treatments at 60 Hz. The efficiency of mass transfer processes appears to be significantly dependent on waveform and frequency of alternating current. Lima and Sastry (1999) and Kulshrestha and Sastry (2003) stated that lowering of electric field frequency for the moderate electric field (MEF) isothermal processing of red beet resulted in higher tissue damage and improved the mass transfer processes. The use of the low-frequency electric field can cause an intensive cell membrane electroporation, leading to a problematic electrical conductivity rise with affected product texture. Samples exposed to the low-frequency electric field showed faster electro-thermal damage rates. Moreover, a non-linear conductivity rise was noticed at high temperatures due to a residual electroporation and thermal plasmolysis. Peach processing at frequencies in the range of tens of kHz acknowledges for an important removal of electroporation. However, rather low tissue electrical conductivity at such frequencies severely increases the time required to achieve the end-point temperature (Shynkaryk *et al.*, 2010). When vegetable tissue is heated, structural changes like cell wall breakdown, tissue damage, increase of mobile moisture and softening occurs, affecting the electrical conductivity (Wang and Sastry, 1997). Thus heating causes more mobile moisture, increasing ionic mobility, which in turn increases the electrical conductivity.

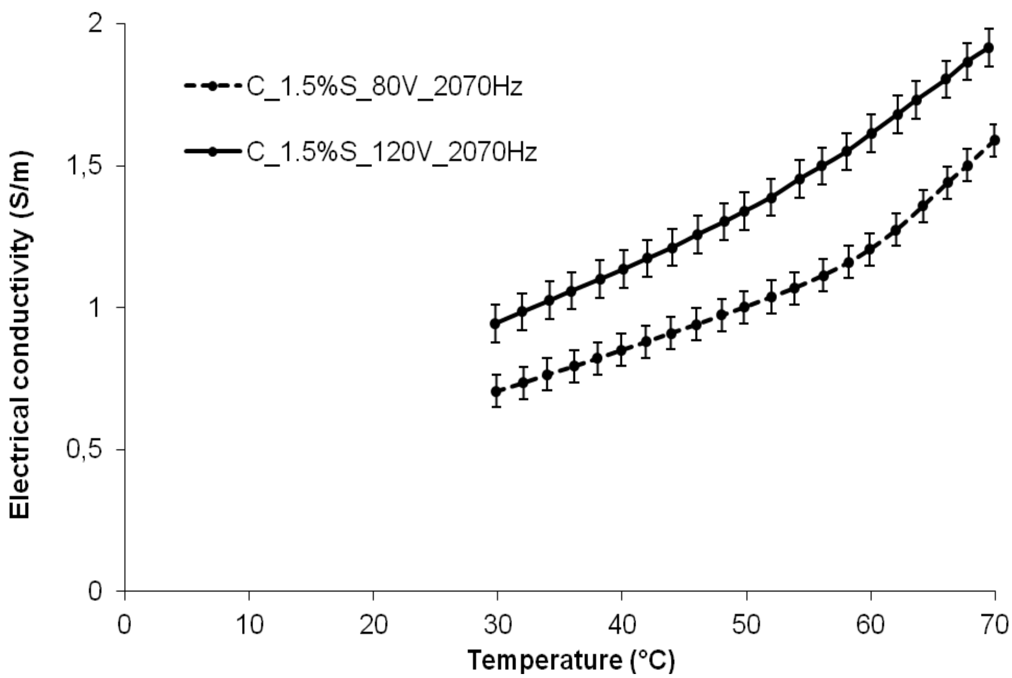
Also, during ohmic heating, slight electrode corrosion occurs mainly via electro-dissolution induced by the low-frequency AC (Ramaswamy *et al*., 2014). The use of a food-compatible electrode electrical material and the correct current density has eliminated contamination problems. Other ways to overcome this problem include utilizing high power frequency, since at alternating frequencies above 100 kHz there is no apparent metal dissolution. Pacific whiting surimi paste and stabilized mince in the 20-70°C range were tested at 80 and 120 V and at five frequency levels (55 Hz, 500 Hz, 5 kHz, 50 kHz, and 200 kHz) by Wu *et al.* (1998). They found that sample electrical conductivity increased slightly with frequency. Electrolytic corrosion at electrode surface diminished with frequency. Such a reaction would cause a burned product and corrosion of the electrode. Their study experienced this problem with all samples tested at 55 and 500 Hz. The corrosion appeared as a light brown porous film in an irregular pattern at low salt concentrations (1%), which became more uniform at higher salt concentrations. As frequency exceeded 500 Hz, they observed that corrosion diminished, as reported by others (Uemura *et al.*, 1994; Reznik, 1996). When conducting experiments at 5 kHz and higher, the corrosion on the electrode surface and burning of the sample were no longer visible. Kulshrestha and Sastry (2006) investigated ohmic heating effects's effect on cell membranes of cellular food material by measurement of dielectric spectra from 100 Hz to 20 kHz of potato in a static ohmic heating cell to various temperatures ranging from 30 to 70°C. Their results show that there was no relation between frequency and changing in value of electrical conductivity. Lima *et al.* (1999) demonstrated that electrical conductivity of turnip tissue is higher at low frequency (at 4 Hz compared to 60Hz). Frequency dependency of the electrical conductivity of plant tissue can be explained by electrical properties of a cell membrane, which can be represented as a resistor and capacitor (Angersbach *et al.*, 1999). Increased permeability or mobility of molecules caused by the applied electric field increases tissue electrical conductivity. It is possible that at lower frequency, the longer polarity change cycle provides sufficient time to induce enough membrane potential to cause electro-permeabilization effects. During electro-permeabilization, it is thought that pores are formed by local polarization of the cell membrane when it is exposed to high electric potential (Zaid *et al.*, 1999).

3.4.3 ELECTRICAL CONDUCTIVITY AS AFFECTED BY VOLTAGE

Figure 3.4 shows voltage and temperature effect on electrical conductivities of two-phase food systems. Each experimental condition was done in two replicates. A broad range of electrical conductivities were found for voltage from 65 to 135 V and temperature from 30 to 70°C: (a) from 0.50 to 1.00 S/m from 30 to 70°C at 80 V and from 0.61 to 1.26 S/m from 30 to 70°C at 120 V; (b) from 0.70 to 1.57 S/m from 30 to 70°C at 80 V and from 0.93 to 1.92 S/m from 30 to 70°C at 120 V. The general trend was that the magnitude of the electrical conductivity increased with temperature and voltage. Electrical conductivities were found to increase quadratically with temperature in all cases. A slight slope change was observed in all cases between 50 and 60°C.



a) Cabbage solutions



b) Daikon radish solutions

Figure 3.4. Voltage effect in electrical conductivities of two-phase food systems; a) Cabbage solutions, b) Daikon radish solutions

Palaniappan and Sastry (1991a) studied the electrical conductivity curves for vegetable tissue and noticed that they presented non-linear styles when decreasing the voltage gradient. Under zero voltage gradient, a cutting transition at about 70°C was reported to be observed, agreeing with compelling softening of the tissue. They justified the electrical conductivity increase with voltage gradient by electro-osmotic effects. The explanation for increasing electrical conductivity with increasing applied voltage turns out to be for the most principally caused by electro-osmotic effects (Halden *et al.*, 1990). The use of voltage develops in fluid movement through the capillaries because biological tissue corresponds to a huge collection of porous membranes. The osmotic pressure exerted across a straight capillary has been illustrated, in an abridged study, to be directly proportional to the voltage gradient (Crow, 1988). Halden *et al.* (1990) recorded conductance while blanching vegetables and implied that the demolition of cell walls lets go the cytoplasm and alters the conductance. Castro *et al.* (2003) investigated the effects of voltage on electrical conductivity of strawberry products. Electrical conductivity increased with temperature for all the products and conditions tested following linear relations. Electrical conductivity was found to depend on the strawberry-based product. An increase of electrical conductivity with voltage was obvious for two strawberry pulps and strawberry filling but not for strawberry topping or strawberry-apple sauce. Eliot-Godéreaux *et al.* (2001) sterilized cauliflower florets in a 10 kW APV continuous ohmic heating pilot. Ohmic heating treatments gave a product of attractive appearance, with interesting firmness properties and a high proportion of particles > 1 cm. Stabilities at 25°C and 37°C were verified, and in one case, the product was even stable at 55°C. Sarang *et al.* (2008) found that the electrical conductivity of various fruits increased linearly with temperature during ohmic heating at voltage between 15 and 20 V (field strength 19-25 V/cm) using alternating current of 60 Hz. Highly porous materials like apples, pear, and pineapple exhibited lower electrical conductivity than peach and strawberry.

3.4.4 COMBINED EFFECTS OF VARIOUS SYSTEM PARAMETERS ON ELECTRICAL CONDUCTIVITY

Table 3.3 presents experimental values of electrical conductivities at 30°C for cabbage and daikon radish at various set of system parameters. Each value represents an average of two replicates and it is accompanied with its standard deviation obtained also from the two replicates for a specified experimental condition. Of the vegetables examined, daikon radish gave the highest value for electrical conductivity (1.07 S/m at 30°C and 1.85%, 100 V, and 5030 Hz). It was followed by cabbage (0.81 S/m at 30°C and the same set of experimental conditions). Tulsiyan *et al.* (2007) measured the electrical conductivities of the individual components of the chowmein. Results showed that the sauce (2.1 S/m at 27°C) was much more conductive than the vegetables components, i.e., celery (0.1 S/m), water chestnut (0.1 S/m), mushrooms (0.2 S/m), and bean sprouts (0.2 S/m). Various authors (Palaniappan and Sastry, 1991a and b; Fryer *et al.*, 1993; Yongsawatdigul *et al.*, 1995) noticed a clear relationship between temperature and electrical conductivity within a temperature range of 20-100°C. This has useful meaning on the

Table 3.3. Experimental values of electrical conductivities (σ) at 30°C for cabbage and daikon radish at various set of system parameters

System parameters			σ_{30}					
SC (%)	V (V)	F (Hz)	Cabbage			Daikon radish		
0.15	100	5030	**0.00**	±	0.02	**0.01**	±	0.05
0.5	80	2070	**0.30**	±	0.03	**0.17**	±	0.08
0.5	80	7990	**0.07**	±	0.04	**0.13**	±	0.09
0.5	120	2070	**0.16**	±	0.02	**0.25**	±	0.06
0.5	120	7990	**0.16**	±	0.03	**0.23**	±	0.04
1	65	5030	**0.27**	±	0.04	**0.47**	±	0.06
1	100	60	**0.32**	±	0.02	**0.53**	±	0.04
1	100	5030	**0.34**	±	0.02	**0.56**	±	0.05
1	100	10000	**0.34**	±	0.02	**0.48**	±	0.03
1	135	5030	**0.36**	±	0.02	**0.59**	±	0.02
1.5	80	2070	**0.64**	±	0.01	**0.69**	±	0.05
1.5	80	7990	**0.49**	±	0.03	**0.79**	±	0.07
1.5	120	2070	**0.60**	±	0.03	**0.92**	±	0.07
1.5	120	7990	**0.63**	±	0.02	**0.89**	±	0.05
1.85	100	5030	**0.81**	±	0.04	**1.07**	±	0.07

ohmic heating behavior making it more effective at high temperature. Typical values between 0.50-1.2 S/m and 0.7-1.6 S/m, over a temperature of 20-80°C were recorded by Palaniappan and Sastry (1991b) for low viscosity liquids (orange and tomato juice), respectively. In comparison, electrical conductivity of a typical solid food is usually smaller than 0.5 S/m. However, if solid particles are soaked in salt solutions or salt is added (Palaniappan and Sastry, 1991a; Halden *et al.*, 1990), values of electrical conductivities will normally be greater than 0.5 S/m.

A box's central composite orthogonal response surface factorial design for four variables at five levels each was used to evaluate each main effect as well as interaction effects. Table 3.4 presents the four independent variables (factors): temperature (T), voltage (V), salt concentration (SC), and frequency (F), of the two-phase food system in the static ohmic heating cell. The independent variable coded values were -1.68 (lowest level), -1, 0 (middle level), 1 and 1.68 (highest level). The complete design consisted of 30 experimental points which included six replications of the center point to estimate the pure error of the analysis and to predict the lack of fit of the models. The dependent variables (Y) (responses) were assumed to be affected by the four independent variables. Response under observations was electrical conductivity.

Table 3.4. The four independent variables (factors): temperature (T), voltage (V), salt concentration (SC), and frequency (F), of the two-phase food system in the static ohmic heating cell

Salt content	SC	(%)	0.15	0.5	1	1.5	1.85
Temperature	T	(°C)	30	38	50	62	70
Frequency	F	(Hz)	60	2070	5030	7990	10000
Voltage	V	(V)	65	80	100	120	135

The analyses of variance and regression coefficient calculation were carried out using Microsoft Excel. SAS software (1999) was used to fit a second order polynomial equation to the experimental data and it was possible to develop a quadratic polynomial model for describing the effects of independent variables. Then, a stepwise procedure was performed to simplify the models and to generate three dimensional surface plots. Results were analysed to compare experimental values with model predictions. The following equations are the polynomials showing the fitted response surfaces for cabbage in salt solutions (3.8) and daikon radish in salt solutions (3.9):

$$\begin{aligned}\sigma = {} & 8.009\times10^{-1} - 2.677\times10^{-1} C_S - 6.463\times10^{-3} T - 8.976\times10^{-5} F \\ & - 6.988\times10^{-3} V + 2.067\times10^{-1} C_S * C_S + 3.928\times10^{-3} C_S * V \\ & + 1.757\times10^{-4} T * T + 8.091\times10^{-7} F * V\end{aligned} \tag{3.8}$$

$$\begin{aligned}\sigma = {} & -1.529\times10^{-2} + 9.901\times10^{-2} C_S - 1.449\times10^{-2} T + 4.691\times10^{-5} F \\ & - 5.253\times10^{-4} V + 6.372\times10^{-2} C_S * C_S + 5.884\times10^{-3} C_S * V \\ & + 3.419\times10^{-4} T * T - 4.999\times10^{-7} F * V\end{aligned} \tag{3.9}$$

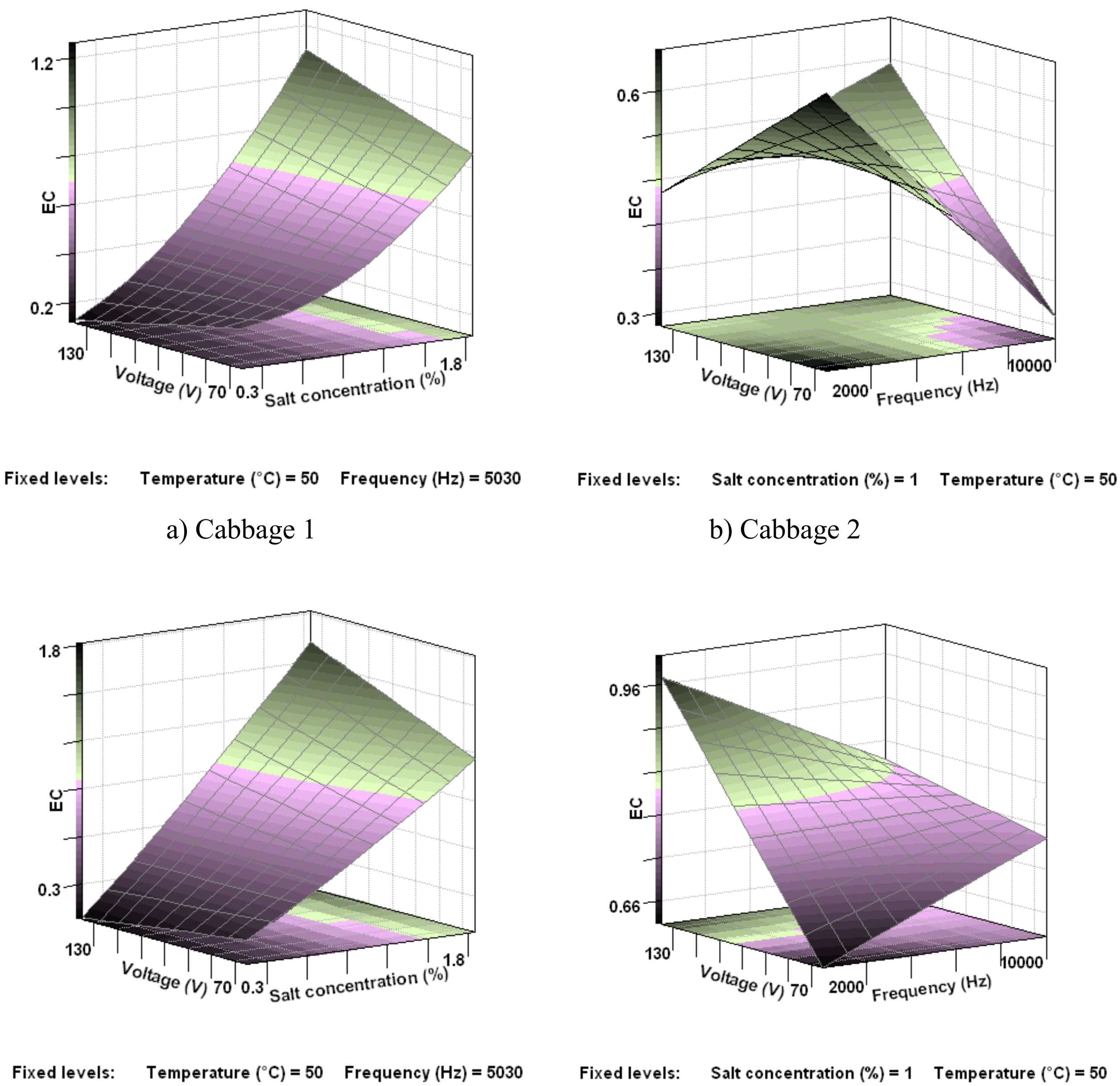
where T is temperature (°C); C_S is salt concentration (%); F is frequency in (Hz); V is voltage (V).

Table 3.5. Statistic results of the correlation between predicted (σ_P, S/m) and measured (σ_m, S/m) electric conductivity of particle-fluid food systems.

Food systems	Regression equation	Statistical result*			
		R^2	SE	P	n
50% (v/v) Cabbage in salt solutions	$\sigma_P = 0.969\sigma_m$	0.978	0.0406	<0.01	29
57% (v/v) Daikon radish in salt solutions	$\sigma_P = 0.966\sigma_m$	0.976	0.0773	<0.01	29

* R^2 is correlation coefficient; SE is standard error; P is probability value of statistical hypothesis; n (DF) is test data number.

The complete response surface model revealed that linear, cross products, and quadratic effects were significant with R^2 over 0.976. Parameters of Equations 3.8 and 3.9 have been used to generate response surface plots showing electrical conductivity as influenced by salt concentration, voltage, and frequency as presented in Figure 3.5. Figure 3.5a shows clearly that



a) Cabbage 1 b) Cabbage 2

c) Daikon radish 1 d) Daikon radish 2

Figure 3.5. Response surface plots for all of the two-phase food system in the static ohmic heating cell; a) Cabbage 1, b) Cabbage 2, c) Daikon radish 1, d) Daikon radish 2

for shredded cabbage the electrical conductivity increases with voltage and salt concentration. In fact, as the voltage is increased, the effect of salt concentration is more important. Also, at very low salt concentration, the electrical conductivity remains almost the same at lower than at higher voltage. But, at high salt concentration, the electrical conductivity increases with the voltage.

Wang and Sastry (1993) investigated the potential for salt diffusion as a pre-treatment for ohmic heating by soaking vegetable (potato) tissue in aqueous NaCl solutions of various concentrations. Electrical conductivity profiles were found to be sensitive to salt concentration profiles at concentrations above 0.01 g/cm^3, but below this concentration conductivity increases were negligible. Figure 3.5b shows that at lower voltage, the electrical conductivity decreases with increasing frequency but that at higher voltage the electrical conductivity increases with increasing frequency. Figure 3.5c shows that for daikon radish, as it was true for shredded cabbage, at higher voltage the electrical conductivity increases more quickly with salt concentration than at lower voltage. Also, as for shredded cabbage, at very low salt concentration, the electrical conductivity remains almost the same at lower than at higher voltage. However, at high salt concentration, the electrical conductivity increases with the voltage. Figure 3.5d is different from Figure 3.5b and shows that at lower voltage, the electrical conductivity increases with increasing frequency but that at higher voltage, the electrical conductivity decreases with increasing frequency. Plots also demonstrated that the magnitude of electrical conductivity is affected by vegetables type.

3.4.5 ELECTRICAL CONDUCTIVITY MODEL

Figure 3.6 compares the measured values and the values predicted by Maxwell-Eucken model 1 ME-1 (Equation 3.3 in Table 3.2) for a system containing 57% (v/v) daikon radish particles (1-cm cubes) dispersed in 0.5% (w/w) saline solution under 80 V and 2070 Hz. The predicted values of electrical conductivity (σ) were obtained from the ME-1 model using the measured electrical conductivity data (σ_L, σ_S) for both components. For a better comparison, the electrical conductivity data measured for the carrier fluid alone and daikon radish in puree form alone are also plotted in Figure 3.6. The electrical conductivity of daikon radish was always less than that of the 0.5% (w/w) salt carrier fluid. For the predicted, measured, and daikon radish alone values, as the temperature increased, the electrical conductivity followed an almost linear rising trend, with a change of slope between 50 and 55°C.

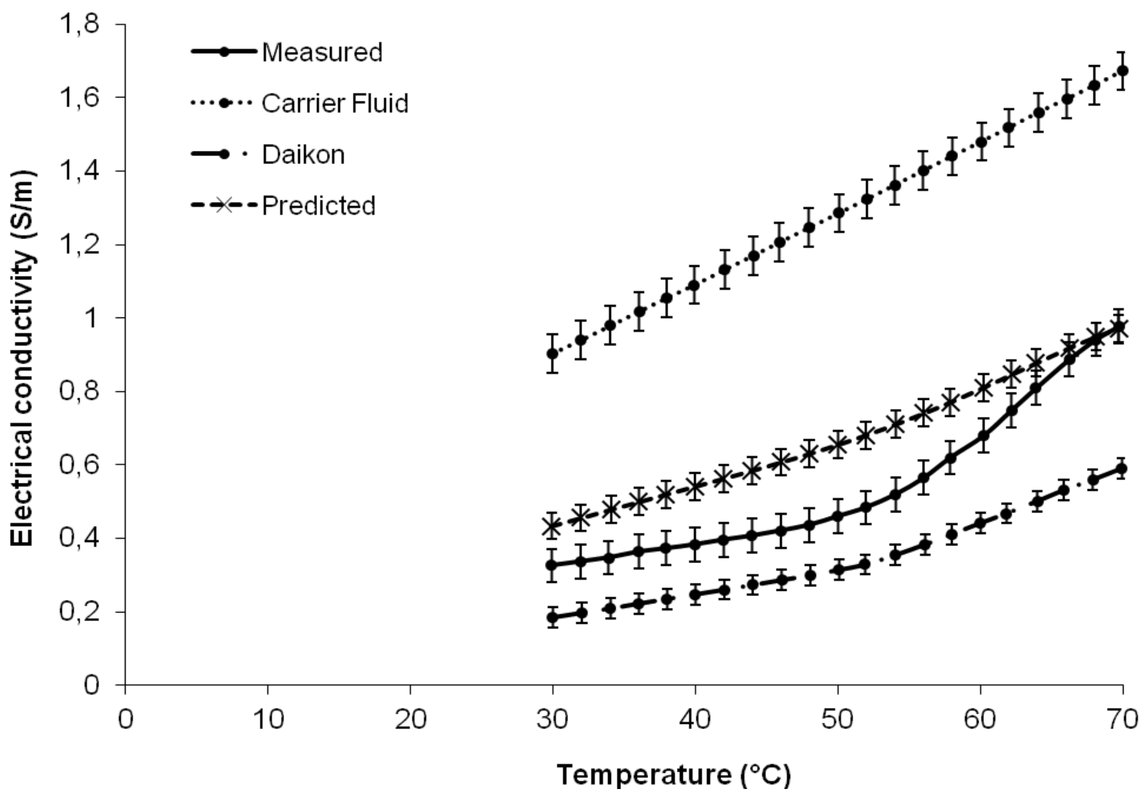


Figure 3.6. A comparison between measured and predicted electric conductivity of food system with 1-cm daikon radish cubes (57%, v/v) dispersed in 0.5%-salt carrier fluid

The ratio of carrier fluid electrical conductivity to daikon radish electrical conductivity was about 5, 4, 3.5, and 3.2 at 35, 45, 55, 65°C, respectively. This means that the 0.5% (w/w) salt carrier had a lower rate of electrical conductivity increase at higher temperatures than the daikon radish did. Both phases have equal contribution to the effective electrical conductivity. However, it can be seen that the continuous phase had a smaller contribution to the measured electrical conductivity value of the two-phase food system. The electrical conductivity of daikon radish was much lower than that of the 0.5% (w/w) salt carrier fluid (Figure 3.6). The mixture of the carrier fluid and daikon radish (57% v/v) gave effective electrical conductivity values between these two-components. The predicted values were slightly higher than the measured one, but the correlations between prediction and measurement were statistically significant ($P < 0.01$) and statistical analysis shows a good correlation between predicted and measured conductivity ($R^2 = 0.9$). In fact, the measured and predicted conductivity are mostly different between 40 and 60°C. Although the two components had a noticeable difference in electrical conductivity values, the model can still generate results that fit the measured effective electrical conductivity curve of the two-phase food system, especially true if the products were blanched.

Zhu *et al.* (2010) predicted effective electrical conductivity from ME-1 model for potato cubes (33% v/v) dispersed in carrier fluids at different salt concentrations. Statistical analysis demonstrated correlations with high coefficients of determination ($0.971 < R^2 < 0.993$) between the measured and predicted effective electrical conductivity values for all three particle-fluid food systems evaluated. Icier and Ilicali (2005) studied apricot and peach purees heated on a laboratory scale static ohmic heater by applying voltage gradients in the range of 20-70 V/cm. The voltage gradient was statistically significant on the ohmic heating rates for both purees ($P < 0.05$). The linear temperature dependent electrical conductivity relations were obtained as was our daikon radish puree.

3.5 CONCLUSIONS

Results from this study give some insight into the electrical conductivity of vegetables suspended in salt solutions as influenced by salt concentration, voltage, frequency, and temperature. As expected, electrical conductivity increased quadratically with temperature. The frequency of alternating current was found to affect the resistance of the tissue as the main constituent of its cell membrane is phospholipid and can be assumed to behave electrically as a condenser. The voltage and the salt concentration influenced electrical conductivity in synergy. Electrical conductivity varied with the vegetables type. Regression equations were established for electrical conductivity as a function of the four factors: salt concentration, voltage, frequency, and temperature. The behavior of vegetable in salt solutions upon ohmic heating is not well understood and is quite different than in conventional heating. Data on e1ectrical conductivities for these products alone (homogenous) and in combination with other compounds (heterogeneous) are needed for the most appropriate selection and for the appropriate design of the ohmic heating process. In this work, some data were obtained which clearly indicated major differences between vegetables type under different set of system parameters upon ohmic heating. Ohmic heating seems to be an excellent substitute to conventional heating when heating vegetables in two-phase systems especially at temperatures under 50°C to minimize cell wall electroporation. The first Maxwell-Eucken model, which describes solid particles dispersed in continuous liquid, showed good agreement between predicted electrical conductivity values and experimental data. This model provided a useful and relatively simple new approach to predict the effective electrical conductivity for two-phase food systems of solid food particles immersed in liquid food.

CHAPTER 4

OHMIC HEATING BEHAVIOR OF CABBAGE AND DAIKON RADISH

4.1 ABSTRACT

Aqueous solutions of two vegetables: one leafy and one root vegetable were selected for ohmic heating testing of two-phase (solid-particles) food systems. Shredded cabbage (50% v/v) and daikon radishes cubes (57% v/v) as well as carrier fluid of different salt concentrations (0.15, 0.5, 1, 1.5, and 1.85%) were heated in a Teflon-coated static ohmic heating cell at different constant voltages of 65, 80, 100, 120, and 135 V. The samples were heated from 30 to 70°C using low and high frequency with an alternating current of 60, 2070, 5030, 7990, and 10000 Hz. Time and temperature data, recorded at selected time intervals, were used to study the effect of salt concentration, voltage, and frequency on the ohmic heating behavior of vegetables in salt solutions. Daikon gave the shortest time to raise the temperature from 30 to 70°C: 6 min at 1.5%, 120 V, 7990 Hz and at 1%, 135 V, 5030 Hz. Cabbage gave the longest time to raise the temperature from 30 to 70°C, 128 min at 0.15%, 100 V, 5030 Hz. Regression analysis resulted in equations where R^2 were greater than 0.98 for heating rates as a quadratic function of the sample temperature for each test material. It indicates the suitability of a quadratic model for heating rates changes with respect to temperature for all types of system parameters. A slight slope change was observed in all cases between 50 and 60°C. As biological tissue is heated, structural changes occur. The cell wall was found to suffer electroporation. The general trend for cabbage solutions was that the magnitude of the heating rate increased with frequency at high voltage, but decreased at low voltage. An opposite trend was observed for daikon radish solutions. Heating rates were found to increase quadratically with temperature in all cases. Heating was more efficient as the salt concentration and the voltage were increased for all vegetables studied. The complete response surface model revealed that linear, cross products, and quadratic effects were significant with R^2 over 0.977. The observed ohmic heating behavior of vegetable solutions corresponded well with their electrical conductivity values.

4.2 INTRODUCTION

The application of aseptic and high temperature short time (HTST) technologies, relying on indirect mechanisms of heat transfer to particulate foods is limited by the time required to conduct sufficient heat into the centre of large particles to ensure sterilisation. Aseptic processing brings liquids with higher overall quality. But there is questions related to continuous aseptic processing of particulate foods resulting in the liquid phase transferring heat to the solid phase. On the other hand, ohmic heating is a new and non-conventional, alternative technique that resides in heating food by passing a current through it (Ohm's law). The food material caught between electrodes has a role of resistance in the circuit. Most foods contain ionic species such as salts and acids, hence, electric current can be made to pass through the food and generate heat inside it (Palaniappan and Sastry, 1991a). The ohmic heating is able to increase the temperature rapidly and uniformly for both homogeneous products and heterogeneous products. What characterizes a difficult product is its bad heat exchange coefficient imposing a large temperature delta on the wall of the heat exchanger and causing a rapid fouling of the system. In an ohmic application the heat transfer coefficient does not intervene and there is no wall effect.

Ohmic heating seems to be a great substitute to conventional heating when heating two-phase systems. In these systems, many authors have pointed out that the solid particles heat up more rapidly than the liquid (Sastry and Palaniappan, 1992a; Zareifard *et al.*, 2003). This way fluids with suspended particles could be treated as liquids in ohmic heating in which only the temperature of the liquid needs to be controlled (Larkin and Spinak, 1996). Ohmic heating implicates the application of a cyclical potential to a food material, resulting in heat generation due to ionic motion. The development of ohmic heating technology presents a major advance in the continuous processing of particulate food products and especially of fragile products (Dinnage, 1990). The system can be applied to fruits such as whole strawberries and diced fruits and to vegetables such as cauliflower which are incompatible with existing processes. The texture of vegetables is determined by the structure and composition of cellular tissue. The cell wall is the constituent of the tissue which most affects this property (Van Buren, 1979). Many factors can modify the heating rate in an ohmic heating system: electrical properties, specific heat, particle type, size, concentration, shape and orientation in the electric field, and process temperature (Legrand *et al.*, 2007; Marcotte, 1999). The heating rate of particles in a fluid depends on the relative conductivities of the system's phases and the relative volume of those phases (Sarang *et al.*, 2007). Most often, the overall electrical resistance of the food system controls the food heating rate.

Wang and Sastry (1993) were able to determine salt diffusivity in vegetable tissues. Sastry and Palaniappan (1992a) noticed that, subjected to static ohmic heating conditions, particle-liquid mixture heat at different rates depending on the relative conductivities of the phases and their volume fractions. If there are present in low concentration, solids of lower conductivity than liquid will drag behind. On the other hand, under high-concentration conditions, particles may heat faster than the fluid. This can be explained by the fact that as the solid content rises; current ways around the fluid get more arduous, obligating a larger proportion of the current to head through the particles. This can end up in a greater energy generation rates within the particles and subsequently a greater relative particle heating rate. Consistent to current literatures, plant products are most appropriate and most often used for ohmic heating processing (Leadley, 2008). In most cases, fruit and vegetables have enough conductivity to attain the required temperatures in less than one minute at comparatively low electric field strengths (Palaniappan and Sastry, 1991a; Wang and Sastry, 1997; Sarang *et al.*, 2008). As biological tissue is heated, structural changes occur (e.g., cell wall protopectin breakdown, expulsion of nonconductive gas bubbles, softening, and tissue damage) that increase ionic mobility (Sasson and Monselise, 1977). Electroporation belief foresees higher damage for tissue with larger cells. Vegetable tissue thermal treatment is recognized to induce apparent damage to cell membranes and to improve mass transfer processes (Lebovka *et al.*, 2007a and b).

Amongst the principal causes of electrical conductivity changes in foods during ohmic heating, the destabilization of cellular membranes is pointed to be the main responsible effect for the reduction of the system's impedance (An and King, 2007; Imai *et al.*, 1995); 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 (Pongviratchai and Park, 2007), among other factors. The nature of the effects observed in plant tissues during ohmic heating is rather complex and is not completely understood, although it was assumed that the electrical breakdown or electroporation mechanism is dominant (Wang and Sastry, 2002; Kulshrestha and Sastry, 2003; Sensoy and Sastry, 2004a). The time of thermal impact necessary to attain a high level of damage relies upon the temperature and varies by individual differences in fruit and vegetables. Solid food like plant tissue is composed of individual cell units and surrounded by their cell membrane and cell wall. The major component of the cell membrane is phospholipid and can be assumed to behave electrically as a condenser. Therefore, it is likely that the frequency of alternating current may affect the resistance of the tissue. Increased permeability or mobility of molecules caused by the applied electric field increases tissue electrical conductivity. It is possible that at lower frequency, the longer polarity change cycle provides sufficient time to induce enough membrane potential to cause electro-permeabilization effects. During electro-permeabilization, it is thought that pores are formed by local polarization of the cell membrane when it is exposed to high electric potential.

The objectives of this chapter were as follows:

a) to determine time/temperature profiles and;

b) to evaluate the heating rate influenced by various system parameters (individual effects, interactions) of selected vegetables during ohmic heating in a static cell in order to have a more comprehensive understanding of their suitability for ohmic heating.

4.3 MATERIALS AND METHODS

4.3.1 EXPERIMENTAL SYSTEM

Figure 4.1 represents experimental set-up and schematics of the static ohmic heating cell used. The same cylindrical Teflon cylinder connected to the same power control unit, data logger, and insulated thermocouples as detailed in Chapter 3 § 3.3.1 were used for the experiments. Voltage and alternating current were also supplied and controlled by the power unit described in Chapter 3 § 3.3.1. As well, thin flexible and rigid Teflon-insulated thermocouples were strategically positioned to monitor the temperature of the liquid medium and the solid particles as explained in Chapter 3 § 3.3.1. Thermal lags due to the Teflon coating of the thermocouples were corrected as described in Chapter 3 § 3.3.1.

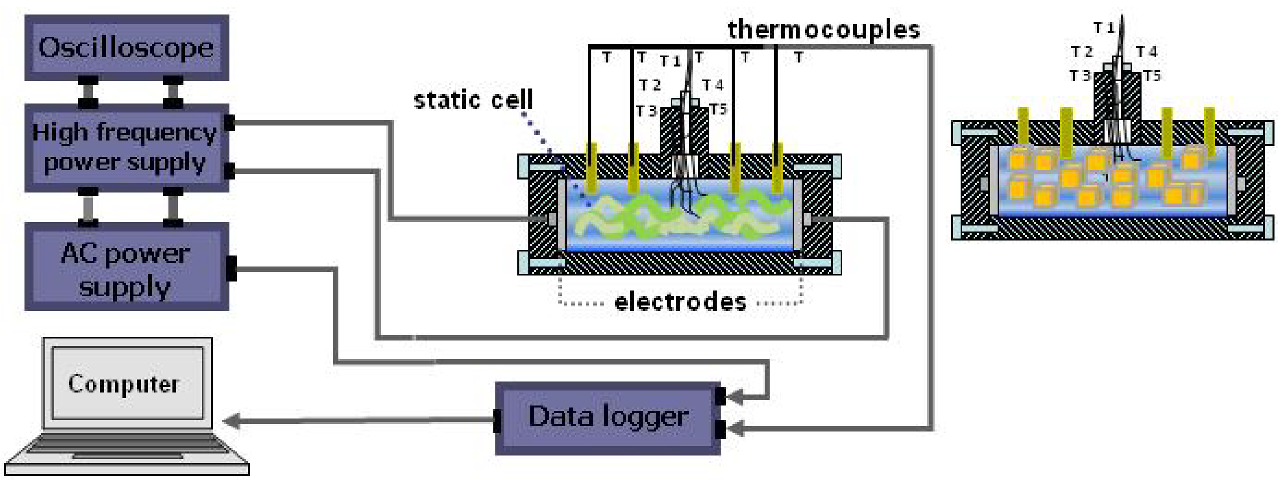


Figure 4.1. Experimental set-up and schematics of the ohmic heating experimental system

4.3.2 SAMPLE PREPARATION

One type of food formulation was used in the experimental study: solid food articles in carrier fluid containing salt at different concentrations (Table 4.1). Fresh vegetables (cabbage and daikon radish, or white radish) were purchased from the same local supplier and peeled, manually cut and shredded as described in Chapter 3 § 3.3.2.

Table 4.1. Samples of food systems prepared for ohmic heating experiments

Materials tested	Salt concentration (%, w/w)	Particle concentration (%, v/v)	Particle size
Particles in carrier fluid	0.15, 0.5, 1.0, 1.5, 1.85	57 (daikon radish)	1-cm cube
	0.15, 0.5, 1.0, 1.5, 1.85	50 (cabbage)	Shredded ± (2 x 5 x 80) mm^3

Two-phase food systems were tested using carrier fluid with various solid phase conditions (Table 4.1). Particles were fouled into the cell in order to have the same mixtures concentrations as described in Chapter 3 § 3.3.2. The same thermocouple installation was made as detailed in Chapter 3 § 3.3.2 for four cubic particles to monitor the temperature profiles of the solid phase during the process. As well, the temperatures were monitored before the experiment started in order to obtain uniform initial temperature conditions. In order to calculate the electrical conductivity that will determine the heating rate, the same assumption was made for shredded cabbage as described in Chapter 3 § 3.3.2. Also, as well as daikon radish in Chapter 3 § 3.3.2, no such assumption was made and a volumetrically integration was used to measure the effective temperature of the static ohmic unit cell based on the mean temperature of the liquid and the particles.

4.3.3 DATA GATHERING

At the beginning of each experiment, particles were fouled into the cell in order to have shredded cabbage (50% v/v) and daikon radishes cubes (57% v/v) and carrier fluid containing different salt concentrations (0.15, 0.5, 1, 1.5, and 1.85%) was poured to fill the empty space of the ohmic heating cell. The sample was heated from 30 to 70°C using an alternating current of 60, 2070, 5030, 7990, and 10000 Hz at different constant voltages of 65, 80, 100, 120, and 135 V. During the experiment, time, temperature, voltage, and current data were recorded at selected time intervals on a Bectrol data logger connected to a computer. Values of voltage and current were used to calculate electrical conductivities using Palaniappan and Sastry's (1991a) method. Time/temperature profiles were plotted and compared for vegetables type. All experiments were performed in duplicates. Experimental heating rates were obtained by calculating the slopes of the tangents to the curve of temperature against time, giving values of dT/dt directly at time intervals.

4.3.4 HEATING RATE

The rate of ohmic heating is directly proportional to the square of the electric field strength and the electrical conductivity (Sastry and Palaniappan, 1992a). The ohmic heating rate is calculated from the electric field intensity, the electrical conductivity, the density and the specific heat of the food product. Therefore, the heating rate depends largely on the physical properties of the food, more specifically on the electrical conductivity. In the absence of other significant heat transfer mechanisms such as convection or/and conduction, neglecting heat losses to the surroundings and using constant voltage conditions, the heating rate can be calculated (Reznik, 1996):

$$\frac{dT}{dt} = \frac{\sigma\left(\nabla V\right)^2}{\rho \, \mathrm{C}_p} \tag{4.1}$$

where T is the temperature (°C); t is the time (min); σ is the electrical conductivity (S/m); ∇ V = E is the voltage gradient (V/m) or electric field intensity; ρ is the density (kg/m^3); Cp is the specific heat (J/kg °C).

4.4 RESULTS AND DISCUSSION

4.4.1 EXPERIMENTAL DATA AT VARIOUS EXPERIMENTAL PARAMETERS

Tables 4.2 and 4.3 show empirically modeled regression equations of heating rates for 50% cabbage (v/v) and 57% (v/v) daikon radish, both in salt solutions, respectively. Each value represents an average of two replicates and is accompanied with its standard deviation obtained also from two replicates. Regression analysis resulted in equations where R^2 were always greater than 0.98 for heating rates as a quadratic function of the temperature. It indicates the suitability of a quadratic model for heating rates changes with respect to temperature for all set of experimental parameters.

Table 4.2. Regression equations of heating rates (HR, °C/min) for 50% (v/v) cabbage in salt solutions

System parameters			Regression equation	Statistical result*			
SC (%)	V (V)	F (Hz)	$x = T < 70$	R^2	SE	P	n (DF)
0.15	100	5030	$HR = -8.693 \cdot 10^{-5}x^2 + 1.333 \cdot 10^{-2}x - 0.140$	0.982	0.012	< 0.01	264
0.5	80	2070	$HR = -2.114 \cdot 10^{-4}x^2 + 4.114 \cdot 10^{-2}x - 0.234$	0.999	0.004	< 0.01	73
0.5	80	7990	$HR = -3.118 \cdot 10^{-5}x^2 + 7.614 \cdot 10^{-3}x + 0.147$	0.997	0.004	< 0.01	190
0.5	120	2070	$HR = -7.721 \cdot 10^{-5}x^2 + 1.867 \cdot 10^{-2}x + 0.403$	0.999	0.006	< 0.01	269
0.5	120	7990	$HR = -1.088 \cdot 10^{-4}x^2 + 2.693 \cdot 10^{-2}x + 0.438$	0.999	0.005	< 0.01	173
1	65	5030	$HR = -1.148 \cdot 10^{-5}x^2 + 4.173 \cdot 10^{-3}x + 0.296$	0.998	0.002	< 0.01	265
1	100	60	$HR = -1.079 \cdot 10^{-4}x^2 + 2.753 \cdot 10^{-2}x + 0.514$	0.999	0.007	< 0.01	160
1	100	5030	$HR = -9.095 \cdot 10^{-5}x^2 + 2.541 \cdot 10^{-2}x + 0.698$	0.999	0.008	< 0.01	155
1	100	10000	$HR = -8.535 \cdot 10^{-5}x^2 + 2.571 \cdot 10^{-2}x + 0.904$	0.999	0.005	< 0.01	245
1	135	5030	$HR = -5.915 \cdot 10^{-4}x^2 + 1.137 \cdot 10^{-1}x - 0.678$	0.997	0.048	< 0.01	162
1.5	80	2070	$HR = -6.598 \cdot 10^{-5}x^2 + 2.722 \cdot 10^{-2}x + 0.531$	0.999	0.008	< 0.01	158
1.5	80	7990	$HR = -1.153 \cdot 10^{-5}x^2 + 6.872 \cdot 10^{-3}x + 1.142$	0.999	0.002	< 0.01	178
1.5	120	2070	$HR = -3.714 \cdot 10^{-4}x^2 + 8.667 \cdot 10^{-2}x + 0.571$	0.999	0.017	< 0.01	79
1.5	120	7990	$HR = -5.061 \cdot 10^{-4}x^2 + 1.084 \cdot 10^{-1}x + 0.140$	0.999	0.033	< 0.01	127
1.85	100	5030	$HR = -4.071 \cdot 10^{-4}x^2 + 8.853 \cdot 10^{-2}x + 0.437$	0.999	0.025	< 0.01	150

* R^2 is correlation coefficient; SE is standard error; P is probability value of statistical hypothesis; n (DF) is test data number.

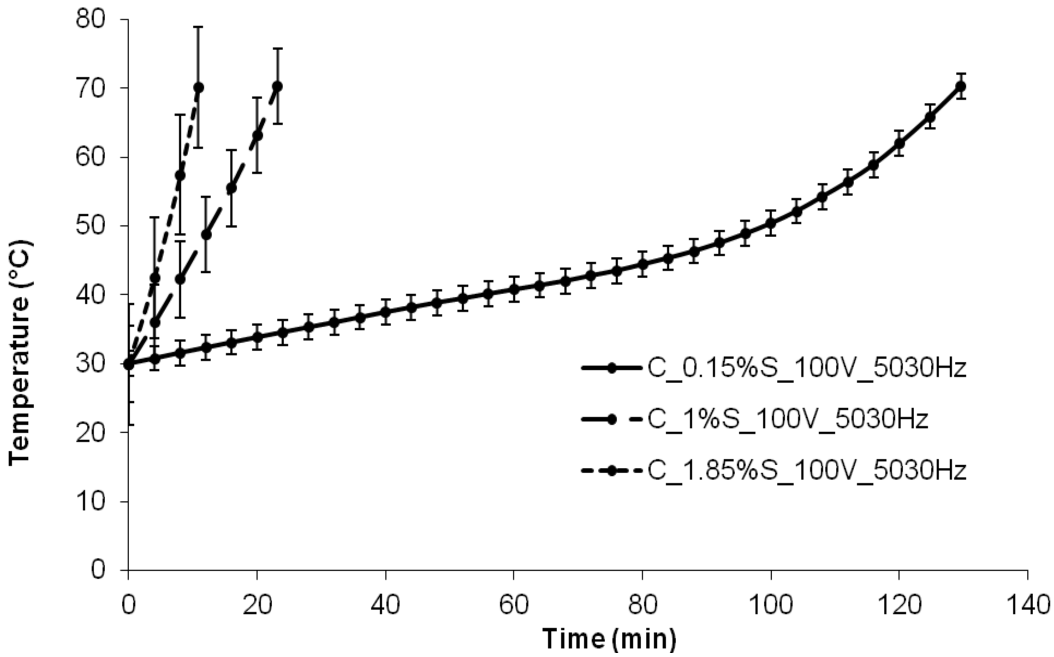
Table 4.3. Regression equations of heating rates (HR, °C/min) for 57% (v/v) daikon radish in salt solutions

System parameters			Regression equation	Statistical result*			
SC (%)	V (V)	F (Hz)	x = T < 70	R^2	SE	P	n (DF)
0.15	100	5030	$HR = -3.635\cdot10^{-5}x^2 + 7.330\cdot10^{-3}x + 0.099$	0.986	0.006	< 0.01	209
0.5	80	2070	$HR = -8.715\cdot10^{-6}x^2 + 3.305\cdot10^{-3}x + 0.409$	0.992	0.003	< 0.01	226
0.5	80	7990	$HR = -4.201\cdot10^{-6}x^2 + 1.999\cdot10^{-3}x + 0.546$	0.992	0.002	< 0.01	185
0.5	120	2070	$HR = -1.962\cdot10^{-4}x^2 + 4.238\cdot10^{-2}x + 0.302$	0.999	0.009	< 0.01	275
0.5	120	7990	$HR = -9.805\cdot10^{-5}x^2 + 2.722\cdot10^{-2}x + 0.972$	0.999	0.008	< 0.01	269
1	65	5030	$HR = -2.014\cdot10^{-6}x^2 + 1.784\cdot10^{-3}x + 0.690$	0.999	0.001	< 0.01	164
1	100	60	$HR = -3.321\cdot10^{-4}x^2 + 6.683\cdot10^{-2}x + 0.104$	0.997	0.030	< 0.01	238
1	100	5030	$HR = -1.787\cdot10^{-4}x^2 + 4.189\cdot10^{-2}x + 0.744$	0.999	0.013	< 0.01	261
1	100	10000	$HR = -1.091\cdot10^{-4}x^2 + 3.093\cdot10^{-2}x + 1.073$	0.999	0.008	< 0.01	249
1	135	5030	$HR = -7.138\cdot10^{-4}x^2 + 1.446\cdot10^{-1}x + 0.147$	0.999	0.048	< 0.01	108
1.5	80	2070	$HR = -8.807\cdot10^{-5}x^2 + 2.468\cdot10^{-2}x + 0.847$	0.999	0.005	< 0.01	159
1.5	80	7990	$HR = -1.476\cdot10^{-4}x^2 + 3.681\cdot10^{-2}x + 0.735$	0.998	0.016	< 0.01	275
1.5	120	2070	$HR = -1.214\cdot10^{-3}x^2 + 2.026\cdot10^{-1}x - 1.183$	0.993	0.144	< 0.01	128
1.5	120	7990	$HR = -1.196\cdot10^{-3}x^2 + 2.137\cdot10^{-1}x - 1.723$	0.995	0.135	< 0.01	124
1.85	100	5030	$HR = -7.899\cdot10^{-4}x^2 + 1.459\cdot10^{-1}x - 0.404$	0.996	0.079	< 0.01	139

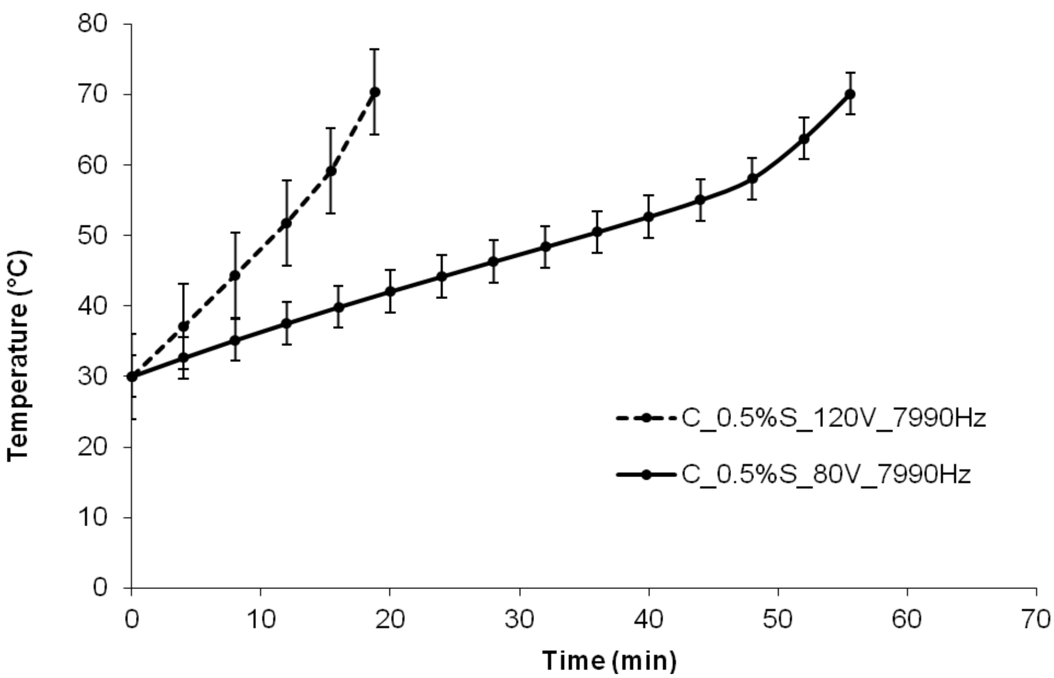
*See Table 4.2 for the description of statistical parameters.

4.4.2 HEATING BEHAVIOR

Typical heating curves for all vegetables are presented on Figure 4.2. The exponential or non-linear heating curves observed are to be expected in a static ohmic heating system because the electrical conductivity (σ) increases substantially with temperature (Palaniappan and Sastry, 1991b). A concave shape of the curve would have indicated that heat losses to the surroundings occurred during ohmic heating. Table 4.4 gives processing times from 30 to 70°C for each vegetables type under various system parameters combinations. Of vegetables examined, daikon radish gave the shortest time to raise the temperature from 30 to 70°C, 6 min at 1.5%, 120 V,



a) Cabbage solutions



b) Daikon radish solutions

Figure 4.2. Typical time/temperature profiles for two-phase food systems; a) Cabbage solutions, b) Daikon radish solutions

7990 Hz and at 1%, 135 V, 5030 Hz. It was closely followed by 7 min at 1.5%, 120 V, 2070 Hz. Cabbage on the other hand had its shortest time of 9 min at 1.85%, 100 V, 5030 Hz. It was closely followed by 10 and 11 min at 1.5%, 120 V, 7990 Hz and at 1%, 135 V, 5030 Hz and at 1.5%, 120 V, 2070 Hz, respectively. It can be said that for both vegetables, at 1.5% and 120 V it gave a rather short processing time but that it was even shorter at higher frequency: 7990 Hz instead of 2070 Hz. Also, for both vegetables it gave the same processing time at 1%, 135 V, 5030 Hz (10 and 6 min). Of vegetables examined, cabbage gave the longest time to raise the temperature from 30 to 70°C, 128 min at 0.15%, 100 V, 5030 Hz. Cabbage gave also it longest time at this operating condition, 93 min. At this condition, the 0.15% salt concentration masked the two other system parameters.

Table 4.4. Processing times from 30-70°C during ohmic heating of vegetables

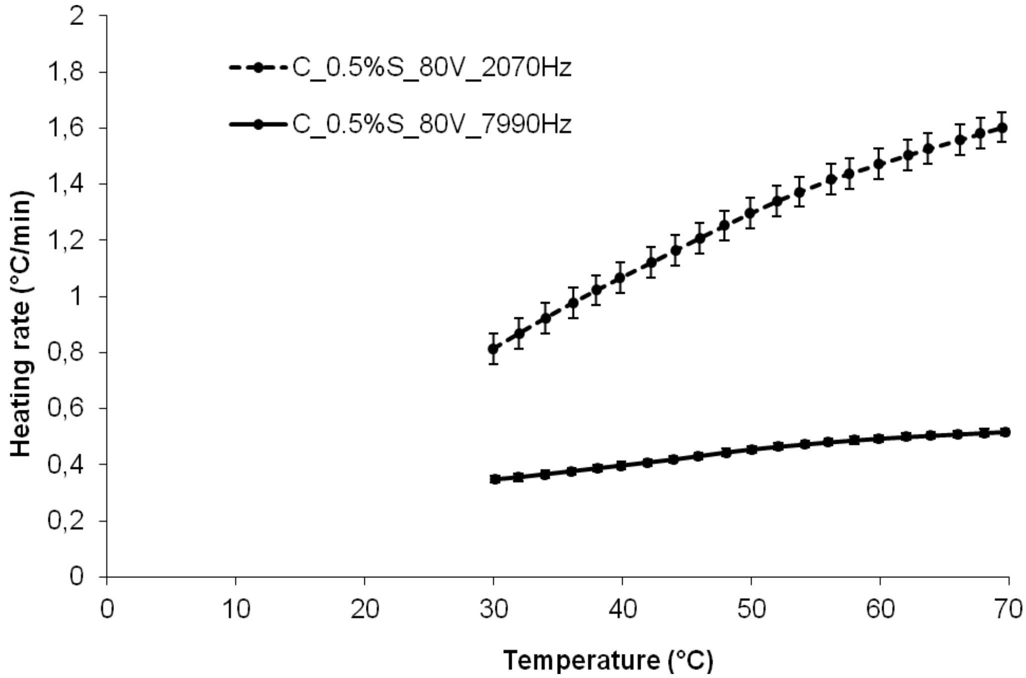
System parameters			Cabbage	Daikon radish
SC (%)	V (V)	F (Hz)	time (min)	
0.15	100	5030	128	93
0.5	80	2070	29	66
0.5	80	7990	85	56
0.5	120	2070	36	20
0.5	120	7990	27	19
1	65	5030	95	50
1	100	60	22	15
1	100	5030	23	16
1	100	10000	18	17
1	135	5030	10	6
1.5	80	2070	24	20
1.5	80	7990	28	18
1.5	120	2070	11	7
1.5	120	7990	10	6
1.85	100	5030	9	10

4.4.3 HEATING RATE AS AFFECTED BY SYSTEM PARAMETERS

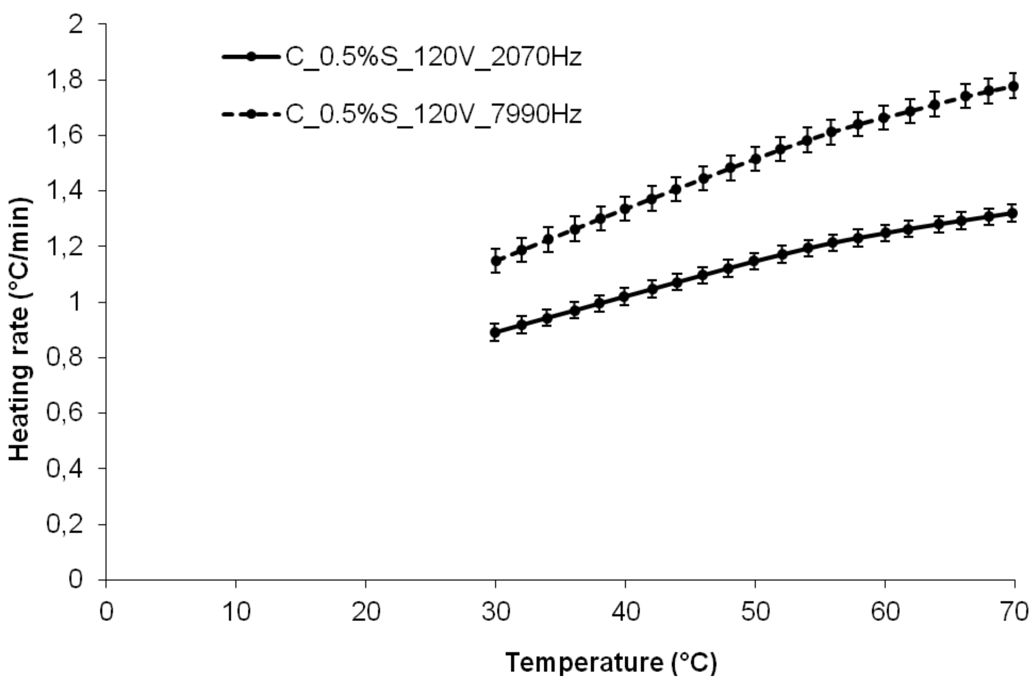
4.4.3.1 HEATING RATE AS AFFECTED BY FREQUENCY

Figure 4.3 shows frequency and temperature effects on heating rate of two-phase food systems. Each experimental condition was done in two replicates. A broad range of heating rates were found from 60 to 10000 Hz and from 30 to 70°C : a) values varied from 0.82 to 1.60°C/min and from 0.35 to 0.53°C/min for 2070 Hz and 7990 Hz, respectively, over the range of processed temperatures of 30 to 70°C; b) values varied from 0.88 to 1.31°C/min and from 1.15 to 1.79°C/min for 2070 Hz and 7990 Hz, respectively, over the range of processed temperatures of 30 to 70°C; c) values varied from 0.48 to 0.57°C/min and from 0.59 to 0.64°C/min for 2070 Hz and 7990 Hz, respectively, over the range of processed temperatures of 30 to 70°C; d) values varied from 1.38 to 2.20°C/min and from 1.69 to 2.33°C/min for 2070 Hz and 7990 Hz, respectively, over the range of processed temperatures of 30 to 70°C. The general trend for cabbage solutions was that the magnitude of the heating rate increased with increasing frequency at high voltage, but decreases at low voltage. For daikon radish solutions, it increased with increasing frequency at both low and high voltages. Heating rates were found to increase quadratically with temperature in all cases. A slight slope change was observed in all cases between 50 and 60°C. It was shown that the time required for reaching the target temperature is dependent upon the frequency, the temperature and the vegetables type.

Ohmic technology has existed for many years but its main handicap was the alteration of electrodes in contact with the product for supply to the main frequency of 50-60 Hz. High frequency technology can alternatively be used to ensure the integrity electrodes. Studies have been made to explain the role of electric field frequency on ohmic heating rate of vegetable food. Lima *et al*. (1999) looked at the electrical conductivity of turnip under ohmic heating at four low-frequencies (4, 10, 25, 60 Hz). They concluded that the heating rate increased with decreasing frequency. Imai *et al*. (1998) found that heating rate of egg albumin solution slightly increased as frequency increased. A maximum heating rate was found at 10 kHz. Food with cellular structure shows different results with changing frequency. Imai *et al*. (1995) have tested the effect of frequency on Japanese white radish. In their study, the lowest frequency (50 Hz) gave the sharpest initial temperature rise. Initial fast heating rate at low frequency is caused by reduced impedance, which is

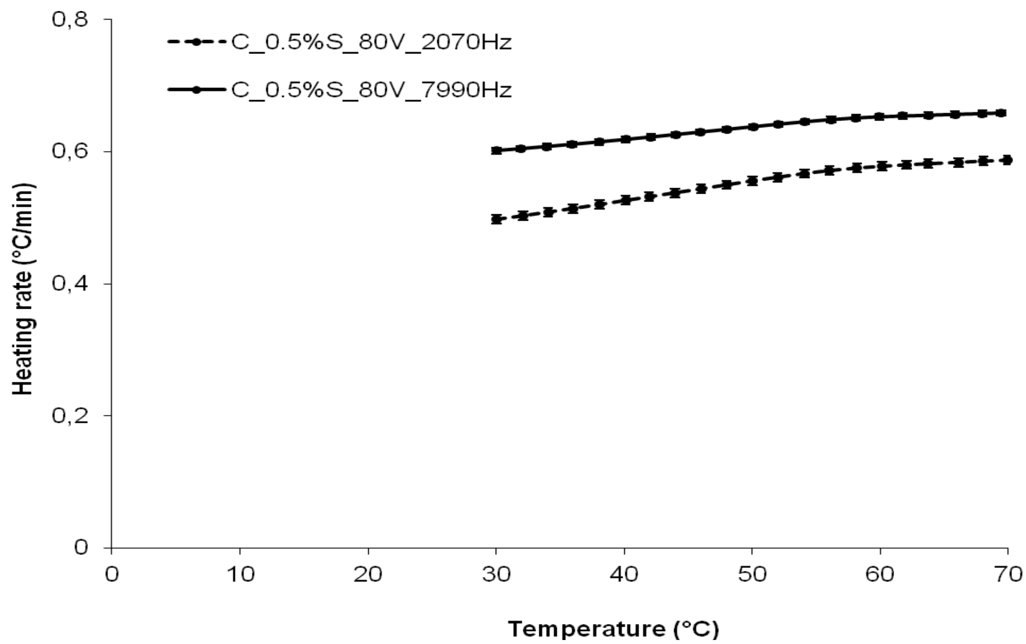


a) Cabbage solutions at low voltage

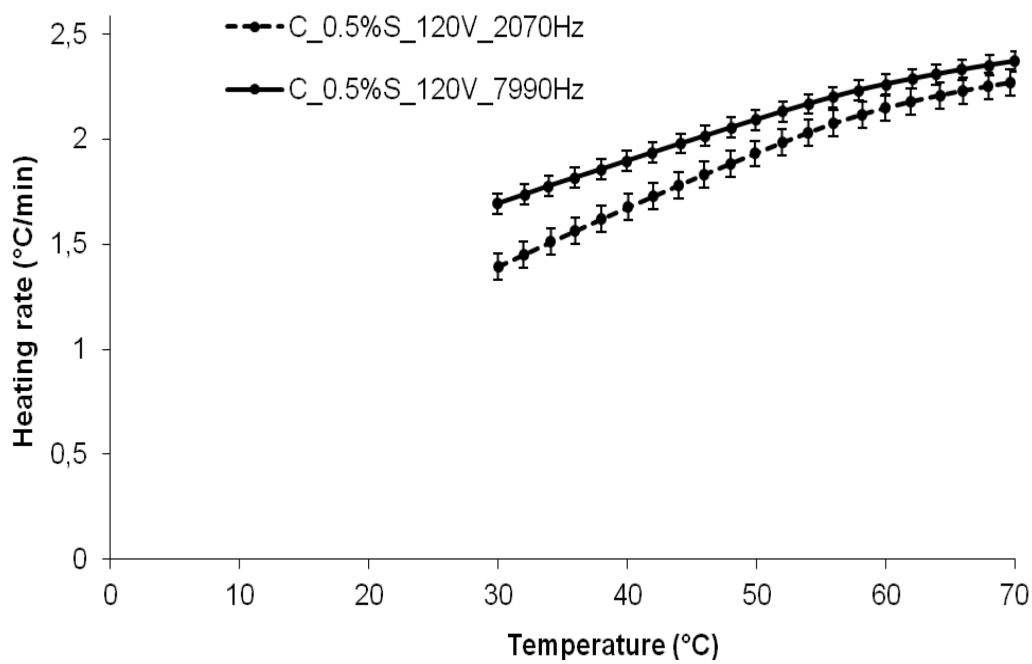


b) Cabbage solutions at high voltage

Figure 4.3. Frequency effect in heating rates of two-phase food systems; a) Cabbage solutions at low voltage, b) Cabbage solutions at high voltage



c) Daikon radish solutions at low voltage



d) Daikon radish solutions at high voltage

Figure 4.3. Frequency effect in heating rates of two-phase food systems; c) Daikon radish solutions at low voltage, d) Daikon radish solutions at high voltage

the result of increased permeability and molecular movement. They observed higher heating rate at lower frequency within the range 50 to 10 kHz and voltage gradient of 40 V/cm. Farahnaky *et al.* (2012) studied the effects of different thermal processing methods (ohmic heating, high and low power, microwave, and conventional heating) on textural properties of cylindrical pieces of root vegetables of carrot, red beet, and golden carrot using texture profile analysis (TPA) technique. They found that not only ohmic heating resulted in greater softening rates but also the final hardness of the samples treated by ohmic heating was significantly lower than those of other samples treated by either conventional or microwave methods. They concluded that ohmic heating can be used for controlled modification of vegetables texture. Moreover, usage of alternating current eliminates the probability of adverse electrochemical reaction. In addition, when the frequency increases, the risk of oxidation in electrodes will decrease.

Lee *et al.* (2013) looked at the effect of frequency of alternating current during ohmic heating on electrode corrosion and on heating rate of vegetables salsa. The impact of waveform on heating rate was also investigated. Salsa was treated with various frequencies (60 to 20 kHz) and waveforms (sine, square, and sawtooth) at constant electric field strength of 12.5 V/cm. Electrode corrosion did not occur when the frequency exceeded 1 kHz. The heating rate of the sample was dependent on frequency up to 500 Hz, but there was no significant difference in the heating rate when the frequency was increased above 1 kHz. The electrical conductivity of the sample increased with a rise in the frequency. At a frequency of 60 Hz, the square wave produced a lower heating rate than that of sine and sawtooth waves. The heating rate between waveforms was not significantly different when the frequency was > 500 Hz. These results suggest that ohmic heating can be effectively used to pasteurize salsa and that the effect of inactivation is dependent on frequency and electrical conductivity rather than waveform.

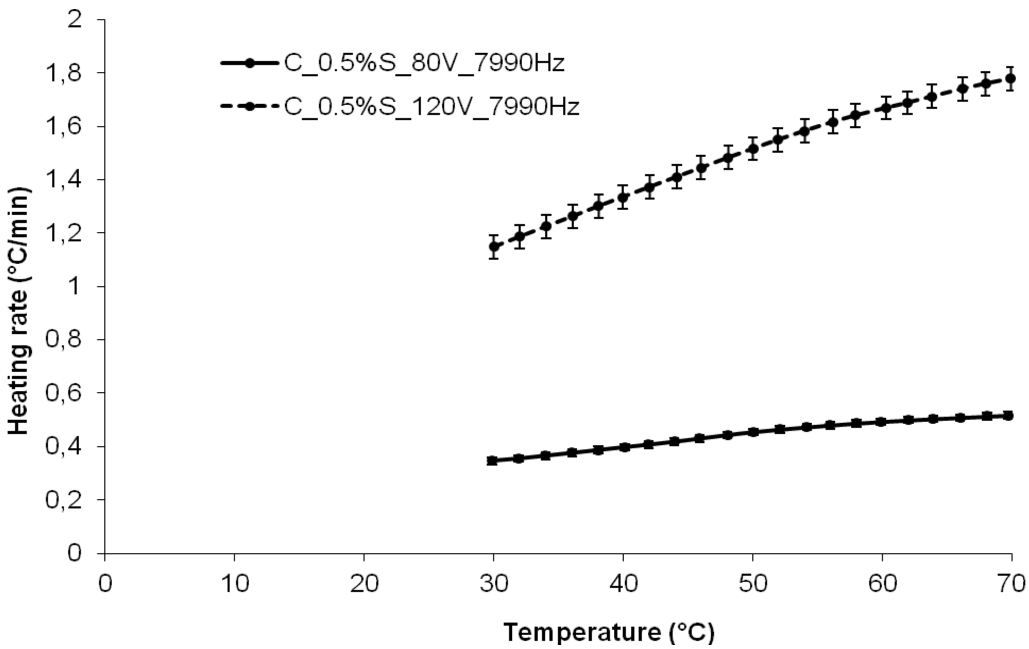
Sensoy and Sastry (2004b) blanched mushrooms during ohmic heating for 11 min 30 s (time required to reach 70°C at the cap center) at 22 V and investigated frequency effects of ohmic heating. They found that the heating rate of hydrated mushroom cylinders at different frequencies (1 to 100 Hz) were not statistically different. Park *et al*. (1995) found that the heating rate of minced fish (Alaska Pollock) increased with frequency, attaining a maximum at 10 kHz, 7.5 times faster than that of a boiled sample. The dielectric loss was found to be maximum at around 10 kHz indicating it would contribute to the quick heating and the better formation of gel.

4.4.3.2 HEATING RATE AS AFFECTED BY VOLTAGE

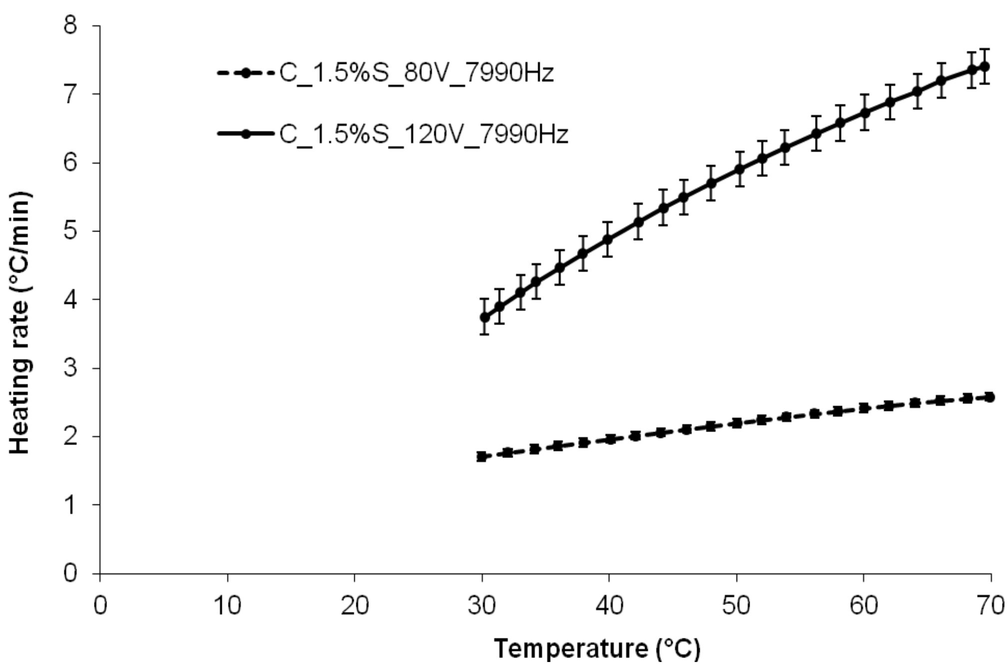
Figure 4.4 shows voltage and temperature effect on heating rates of two-phase food systems. Each experimental condition was done in two replicates. A broad range of heating rates were found from 65 to 135 V and from 30 to 70°C: a) values varied from 0.35 to 0.52°C/min and from 1.17 to 1.78°C/min for 80 V and 120 V, respectively, over the range of processed temperature of 30 to 70°C; b) values varied from 1.75 to 2.55°C/min and from 3.98 to 7.45°C/min for 80 V and 120 V, respectively, over the range of processed temperature of 30 to 70°C. The general trend was that the magnitude of the heating rate increased with temperature and voltage. Heating rates were found to increase quadratically with temperature in all cases.

Ranmode and Kulshreshtha (2011) conducted experiments to study the enhancement of carrot juice recovery using 2-stage pressing with ohmic heating. They found out that ohmic heating can enhance the juice recovery. The study indicated that maximum juice recovery of 98.9% can be obtained with 1st pressing of 2.72 min., ohmic heating up to a final temperature of 65.6°C under a voltage gradient of 15V/cm followed by 2nd pressing of 10 min. Darvishi *et al.* (2012) tested ohmic heating of tomato using five different voltage gradients (6, 8, 10, 12, and 14 V/cm or five voltage inputs: 30, 40, 50, 60, and 70V) at 50 Hz frequency. The electrical conductivity values were in the range of 0.35 to 0.82 S/m having an increasing trend with increasing temperature. Ohmic heating times were dependent on the voltage gradient used. As the voltage gradient increased form 6 to 14 V/cm, time decreased from 235 to 38 s.

Nistor *et al.* (2013) studied the temperature variation of the apple puree treated by batch ohmic heating under different voltage gradients from 15 to 20 V/cm at 50 Hz frequency. They concluded that the heating is more efficient and faster when the voltage gradient is higher. The highest value of the electrical conductivity corresponding to a lower value of time processing has been obtained at a 20 V/cm voltage gradient (1.08 S/m at 65.7°C for 300 s) while



a) Cabbage solutions



b) Daikon radish solutions

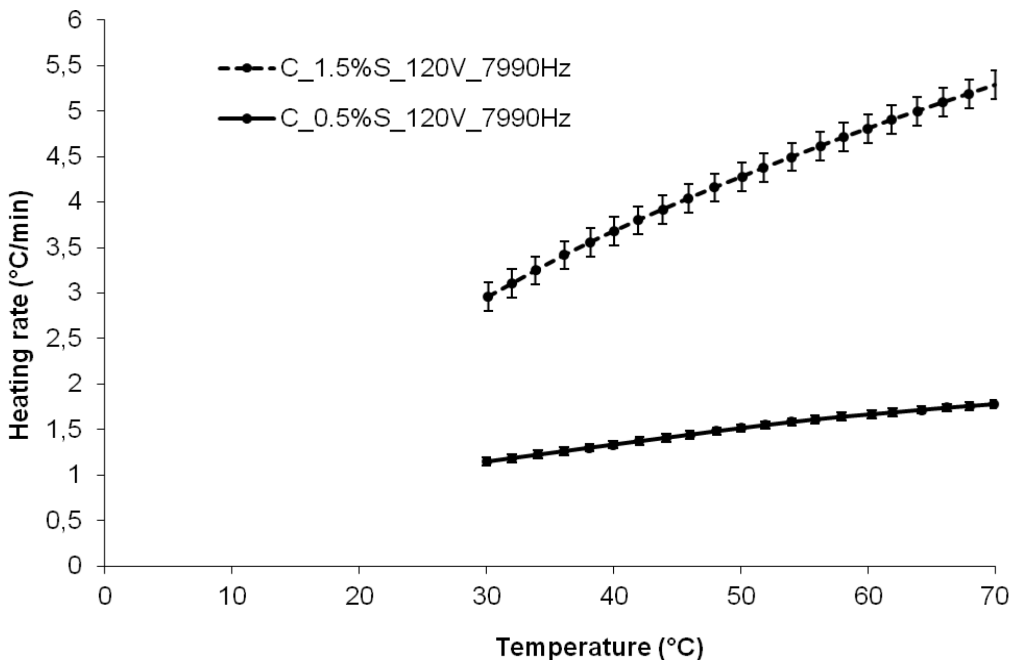
Figure 4.4. Voltage effect in heating rates of two-phase food systems; a) Cabbage solutions, b) Daikon radish solutions

a similar value can be reached at a lower voltage gradient (15, 17, 17.5 V/cm) only in a much longer time, that is 1200 s. In cyclic ohmic heating, the heating rate increased by cycles. Samples preheated by either conventional or ohmic heating showed a higher heating rate than raw materials. Electrical conductivity data during ohmic heating showed that preheated vegetables have higher conductivities than fresh ones, and a tendency of increase by cycles was found (Wang and Sastry, 1997).

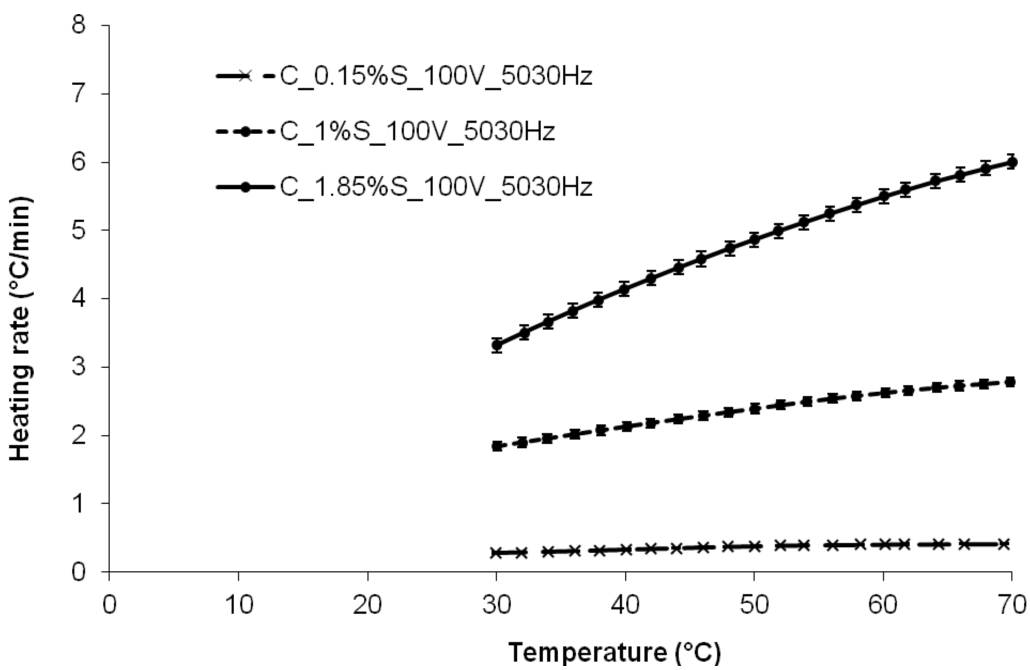
Olivera *et al.* (2013) verified the effects of ohmic heating treatment on texture of fresh potatoes, carrots, and apples (without pre-treatment in brine solutions), subjected to constant voltage gradient (1100, 2200, 3300 V/m) at 50 Hz frequency. Firmness of solid samples decreased with voltage gradient and time. Their treatment in an ohmic heating cell needed electric field strength higher than 1100 V/m. For all the considered food substrate, appreciable firmness disintegration appeared only for voltage strength of 2200 V/m and higher, apple being the food substrate more sensible to the softening effects due to ohmic heating treatment. This study confirmed that ohmic heating significantly affects texture of fruits and vegetables products, producing structural damage, even though food has a low electrical conductivity.

4.4.3.3 HEATING RATE AS AFFECTED BY SALT CONCENTRATION

Figure 4.5 shows salt concentration and temperature effects on heating rates of two-phase food systems. Each experimental condition was done in two replicates. A broad range of heating rate were found from 0.15 to 1.85% of salt concentration and from 30 to 70°C : a) from 1.12 to 1.80°C/min at 30 to 70°C and 0.5%, and from 2.90 to 5.32°C/min at 30 to 70°C and 1.5%; b) from 0.25 to 0.45°C/min at 30 to 70°C and 0.15%, from 1.80 to 2.68°C/min at 30 to 70°C and 1%, and from 3.30 to 5.89°C/min at 30 to 70°C and 1.85%. The general trend was that the magnitude of the heating rate increased with temperature and salt concentration. Heating rates were found to increase quadratically with temperature in all cases.



a) Cabbage solutions



b) Daikon radish solutions

Figure 4.5. Salt concentration effect in heating rates of two-phase food systems; a) Cabbage solutions, b) Daikon radish solutions

4.4.4 COMBINED EFFECTS OF VARIOUS SYSTEM PARAMETERS ON HEATING RATE

A box's central composite orthogonal response surface factorial design for four variables at five levels each was used to evaluate each main effect as well as interaction effects as described in Chapter 3 § 3.4.4. The four independent variables (factors) are listed in Table 3.4. This time, response under observations was heating rate. The analyses of variance and regression coefficient calculation were carried out using the safe software as mentioned in Chapter 3 § 3.4.4.

As well, SAS software (1999) was used to fit a second order polynomial equation to the experimental data and it was possible to develop a quadratic polynomial model for describing the effects of independent variables. Then, stepwise procedure was preformed to simplify the models and to generate seven dimensional surface plots. Results were analysed to compare experimental values with model predictions. The following are the polynomials showing the fitted response surfaces for cabbage in salt solutions (4.2) and daikon radish in salt solutions (4.3):

$$\begin{aligned} HR = {} & 8.549 - 5.201 * C_S - 4.933\times10^{-2} T - 3.589\times10^{-4} F \\ & -1.089\times10^{-1} V + 5.686\times10^{-1} C_S * C_S + 2.053\times10^{-2} C_S * T \\ & + 4.870\times10^{-2} C_S * V + 5.021\times10^{-4} T * V + 3.549\times10^{-6} F * V \\ & + 2.742\times10^{-4} V * V \end{aligned} \tag{4.2}$$

$$\begin{aligned} HR = {} & 7.314 - 5.162 C_S - 3.345\times10^{-2} T - 1.317\times10^{-1} V \\ & + 4.226\times10^{-2} C_S * T + 5.671\times10^{-2} C_S * V - 8.313\times10^{-4} T * T \\ & + 1.043\times10^{-3} T * V + 4.330\times10^{-4} V * V \end{aligned} \tag{4.3}$$

where T is temperature (°C); C_S is salt concentration (%); F is frequency in (Hz); V is voltage (V).

The complete response surface model revealed that linear, cross products, and quadratic effects were significant with R^2 over 0.977 (Table 4.5). Parameters of Equations 4.2 and 4.3 have been used to generate response surface plots showing heating rate as influenced by the four factors as presented (Figures 4.6 and 4.7). Figure 4.6a shows that at lower voltage, the heating rate decreases with increasing frequency but that at higher voltage the heating rate

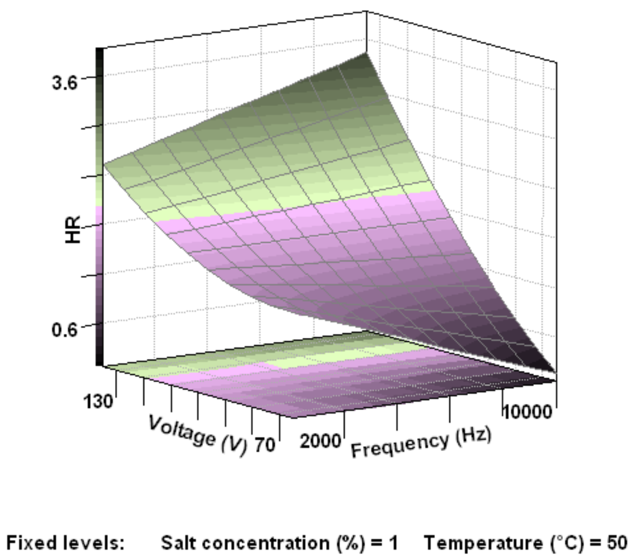
Table 4.5. Statistic results of the correlation between predicted (HR_P, °C/min) and measured (HR_m, °C/min) heating rates of particle-fluid food systems

Food systems	Regression equation	Statistical result*			
		R^2	SE	P	n
50% (v/v) Cabbage in salt solutions	$HR_P = 0.965 HR_m$	0.977	0.2194	<0.01	29
57% (v/v) Daikon radish in salt solutions	$HR_P = 0.983 HR_m$	0.988	0.2245	<0.01	29

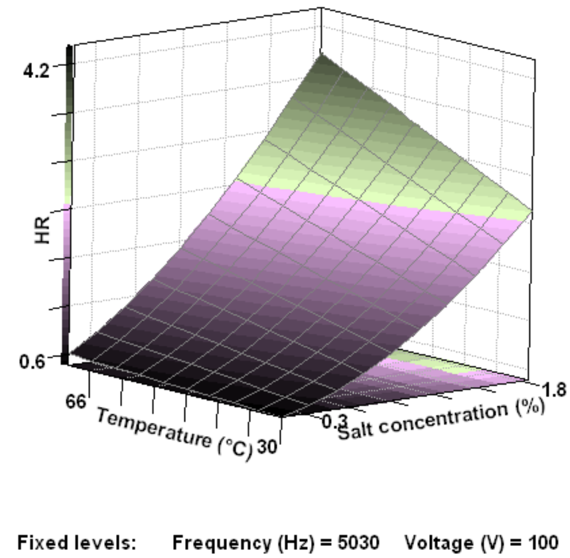
*See Table 4.3 for the description of statistical parameters.

increased with increasing frequency. Figure 4.6b shows that at lower salt concentration, the heating rate remains almost the same although the temperature is increased but that at higher salt concentration the heating rate increases greatly with the temperature. Figure 4.6c shows that the heating rate increases with the temperature and the voltage. Figure 4.6d shows clearly that the heating rate increases with voltage and salt concentration. In fact, as the voltage is increased, the effect of salt concentration is more important. Also, at very low salt concentration, the heating rate remains almost the same at lower than at higher voltage. But, at high salt concentration, the heating rate increases abruptly with the voltage.

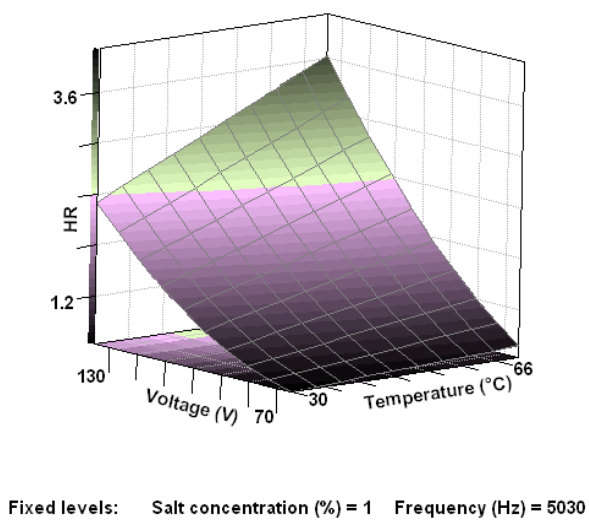
Figure 4.7a and b show that at low voltage or at low salt concentration as the temperature increases, the heating rate remains constant, but that at high voltage or at high salt concentration as the temperature increases, the heating rate also increases. Figure 4.7c shows that a low voltage, as the salt concentration is increased, the heating rate increases slightly, but that at high voltage as the salt concentration is increased, the heating rate raises aggressively. 3D plots also demonstrated that the magnitude of heating rate is affected by vegetables type.



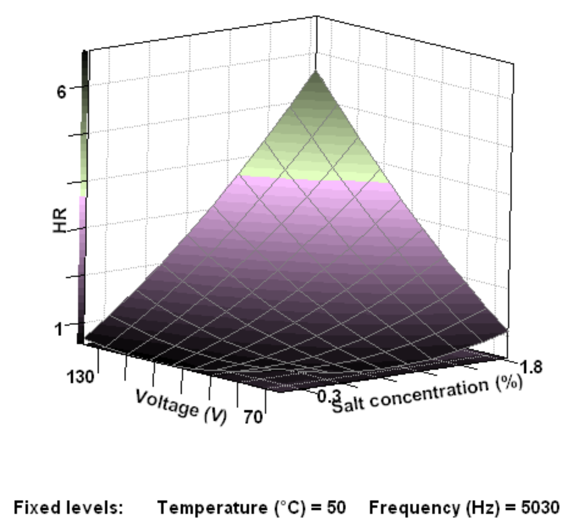
a) Cabbage 1



b) Cabbage 2

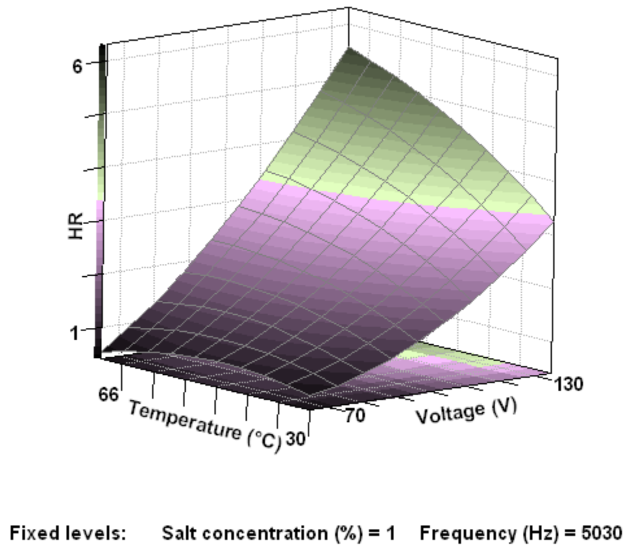


c) Cabbage 3

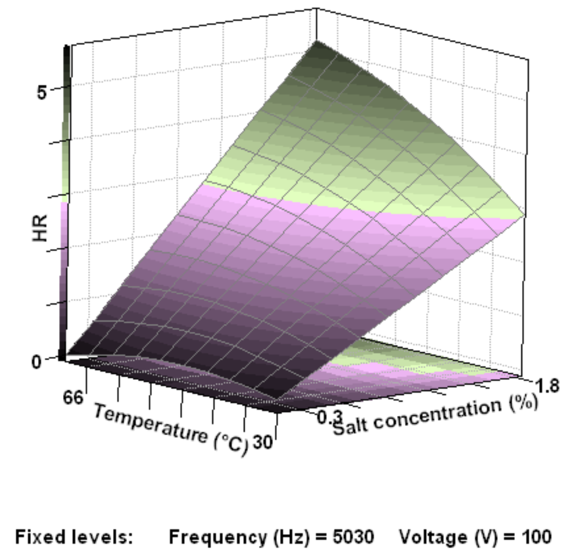


d) Cabbage 4

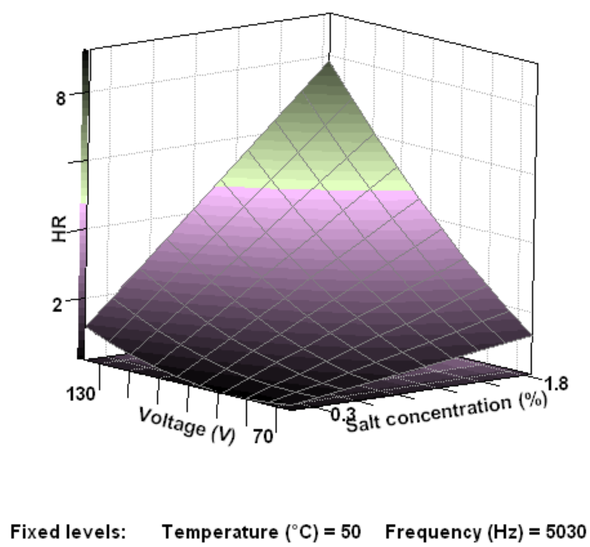
Figure 4.6. Response surface plots for all of cabbage in two-phase food system in the static ohmic heating cell; a) Cabbage 1, b) Cabbage 2, c) Cabbage 3, d) Cabbage 4



a) Daikon radish 1



b) Daikon radish 2



c) Daikon radish 3

Figure 4.7. Response surface plots for all of daikon radish in two-phase food system in the static ohmic heating cell; a) Daikon radish 1, b) Daikon radish 2, c) Daikon radish 3

4.5 CONCLUSIONS

The ohmic heating behavior of selected vegetables solutions was studied as influenced by system parameters. Many factors were found to modify the heating rate in an ohmic heating system: electrical properties, particle type and size, concentration, salt concentration, voltage, temperature, and frequency. Heating rates were found to increase quadratically with temperature in all cases. The frequency of alternating current was found to affect the resistance of the tissue as its main constituent of the cell membrane is phospholipid and can be assumed to behave electrically as a condenser. Experimental conclusions on heating rates were comparable to those reported in the literature for static ohmic heating cell experiments. Ohmic heating seems to be a great substitute to conventional heating when heating two-phase systems under 55°C to prevent cell wall electroporation. Study has been made to explain the role of electric field frequency on ohmic heating rate of vegetables food. A known problem for supply to the main frequency (50-60 Hz) was the alteration of electrodes in contact with the product. High frequency technology can alternatively be used to ensure the integrity of electrodes.

CHAPTER 5

GENERAL CONCLUSIONS

In this thesis, the technical feasibility of ohmic heating for two vegetables in salt solutions was investigated thoroughly. The objectives of the thesis work were to investigate the electrical conductivity and the heating rate of fresh vegetables (cabbage and daikon radish) in the presence of salt solution ohmically processed under different system parameters (frequency of alternating current, voltage, salt concentration, and temperature) and to establish suitable models for a better understanding of the ohmic heating behavior. The study consisted of three main steps: 1) regression models of electrical conductivity and heating rate were developed using central composite design (CCD) with influencing parameters. These were used to represent in 2D and in 3D the individual effects and their interactions; 2) time/temperature profiles were established and the heating behavior was determined as influenced by various system parameters of selected vegetables in order to have a more comprehensive understanding of their suitability for ohmic heating; 3) the Maxwell-Eucken 1 (ME-1) model of solid particles dispersed in a continuous liquid phase was used for electrical conductivity evaluation. The model makes an analogy between heat and electricity for modeling the effective electrical conductivity of particle-fluid mixtures.

Of the two vegetables examined, daikon radish gave the highest value for electrical conductivity (1.07 S/m at 30°C and 1.85%, 100 V, 5030 Hz). It was followed by cabbage (0.81 S/m at 30°C and the same set of experimental conditions). Daikon gave the shortest time to raise the temperature from 30 to 70°C: 6 min at 1.5%, 120 V, 7990 Hz and at 1%, 135 V, 5030 Hz. Cabbage gave the longest time to raise the temperature from 30 to 70°C, 128 min at 0.15%, 100 V, 5030 Hz. Regression analysis resulted in equations where R^2 were greater than 0.98 for heating rates as a quadratic function of the sample temperature for each test material, indicating the suitability of such a model. The frequency of alternating current was found to affect the resistance of the tissue as the main constituent of its cell membrane is phospholipid and can be assumed to behave electrically as a condenser. For cabbage solutions, it was observed that the magnitude of the electrical conductivity increased with increasing frequency at high voltage, but decreases at low voltage. The same trend was observed for the heating rate. Another trend was observed for daikon radish solutions, the magnitude of the electrical conductivity increased with increasing frequency at low voltage, but decreased or remained the same at high voltage and the magnitude of the heating rate increased with frequency at both low and high voltages. Electrical conductivities and heating rates were higher as the salt concentration and the voltage were increased. In fact, as the voltage is increased, the effect of salt concentration is more important and vice versa. As expected, electrical conductivity was found to increase quadratically with temperature. Heating rates were also found to follow a quadratic path. A slight slope change was observed in all cases between 50 and 60°C. As biological tissue is heated, structural changes occur: the cell wall suffers electroporation. The complete response surface models for electrical conductivity and heating rate revealed that some linear, cross products, as well as quadratic effects were significant with R^2 over 0.976 and 0.977, respectively. Electrical conductivities and heating rates were found to vary greatly varied with the vegetables type, whether leafy or root. The observed ohmic heating behavior of vegetable solutions corresponded well with their electrical conductivity values.

The first Maxwell-Eucken model, which describes solid particles dispersed in continuous liquid, showed good agreement between predicted electrical conductivity values and experimental data. This model provided a useful and relatively simple new approach to predict the effective electrical conductivity for two-phase food systems of solid food particles immersed in liquid food. A known problem for supply to the main frequency (50-60 Hz) was the alteration of electrodes in contact with the product. High frequency technology can alternatively be used to ensure the integrity of electrodes. The behavior of vegetable in solutions upon ohmic heating is virtually unknown and probably quite different than in conventional heating. Data on e1ectrical conductivities for these products alone (homogenous) and in combination with other compounds (heterogeneous) are needed for the most appropriate selection and far the appropriate design of the ohmic heating process. In this work, some data were obtained which clearly indicated major differences between vegetables type under different set of system parameters upon ohmic heating. Ohmic heating seems to be a great substitute to conventional heating when heating vegetables in two-phase systems under 50°C to prevent cell wall electroporation.

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