OHMIC HEATING FOR THERMAL PROCESSING OF LOW-ACID
FOODS CONTAINING SOLID PARTICULATES

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
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* * * * *

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ABSTRACT

Ohmic heating has potential applications for continuous sterilization processing of low-acid foods containing particulates. The main challenge is to establish a credible safety assurance protocol through experimental and modeling studies.

The electrical conductivity of food components is critical to ohmic heating. Electrical conductivities of six different fresh fruits (red apple, golden apple, peach, pear, pineapple and strawberry) and several different cuts of three types of meat (chicken, pork and beef) were determined from 25 - 140°C. Electrical conductivity of all products increased linearly with the temperature during ohmic heating at constant voltage gradient. Lower electrical conductivity was observed for porous materials like apples. Lean muscle cuts were much more conductive than the separable fat. There was no strong relationship between the measured fat content of the lean muscle cuts and their electrical conductivity suggesting that fat distribution or marbling might be an important factor affecting the electrical conductivity of meat.

Heating rates of solid and liquid phases during ohmic heating depend on the electrical conductivities of both phases. An ideal processing condition can be achieved when conductivities of both the phases are equal, since, under such a condition, both phases will heat at the same rate. For a chicken chowmein (low-acid food product containing particulates) it was observed that the sauce was more conductive than all the
solid components (chicken, celery, mushroom, water chestnut and bean sprouts). A simple blanching method was developed to increase the electrical conductivity of solid components. Except chicken, it was possible to adjust the conductivity of all solids close to that of the sauce by blanching solids in highly conductive sauce at boiling temperature. Chicken chowmein product containing blanched solids and another product containing untreated solids were heated ohmically in a bench-scale static ohmic heater. All components of the treated product containing blanched solids heated more uniformly compared to the product containing untreated solids. Sensory test results showed that the blanched product was of good quality and had good overall acceptability. Thus, on adjusting the electrical properties of different components it may be possible to ensure more uniform heating while still maintaining product quality.

Enhancement of electrical conductivity of solid particulate foods could be achieved by salt infusion. The knowledge of diffusivity of salts in food solids would enable the determination of the pretreatment conditions necessary for ohmic heating. A simple method was developed to measure diffusivity of salt in water chestnut tissue under different levels of sodium chloride concentration and temperature. The apparent diffusion coefficient of salt in water chestnut did not change significantly with salt concentration, but as expected it increased significantly with temperature. Diffusion data were further used to solve the mass transfer problem, using Computational Fluid Dynamics (CFD) software, to predict salt concentration profile in a 3D water chestnut disc under different conditions. It was observed that after pretreatment (blanching for 90 s in salt solution at boiling temperature) salt diffused only to a certain depth in the disc and the salt concentration in the interior is essentially zero. Thus, even though it is possible to
increase the overall ionic content and electrical conductivity of solids by blanching in highly conductive sauce, conductivity may not be uniform within the solids. However, even this limited diffusion is useful in improving solids heating.

Measurement of residence time distribution (RTD) is needed for determination of the fastest-moving particle, to be used for designing and biologically validating processes. Radio Frequency Identification (RFID) was used to measure residence time distribution (RTD) of particles in the ohmic heater in a continuous sterilization process. The residence times and the residence time distribution of a model food particle system (potato in starch solution) were investigated in the ohmic heater. The effect of six levels of solid concentration and three levels of rotational speed of the agitators on the RTD were studied. Mean particle residence time increased with the rotational speed of agitators in the ohmic heaters. Mean particle velocities were greater than the mean product velocity. The velocity of the fastest particle was 1.62 times the mean product velocity which is less than that associated with Newtonian fluid in tubular flow.
Dedicated to my parents
I would like to express my sincere appreciation and gratitude to my advisor, Dr. Sudhir Sastry for his guidance throughout with my dissertation. Special thanks to him for supporting me during toughest time in my life. I also extend my gratitude to Drs. BalaBalsubramaniam, Ahmed Yousef and Harold Keener, dissertation committee, for their valuable comments and remarks. I acknowledge the technical assistance by Brian Heskitt.

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CHAPTER 1

INTRODUCTION

Continuous sterilization of low-acid foods (pH>4.6, water activity>0.85, stored at nonrefrigerated temperature) containing particulates, where *Clostridium botulinum* is the target pathogen, is of great interest to the food industry. Since the early nineteenth century the preferred method for microbial destruction in foods has been heat, either in cans or via aseptic processing using conventional heat exchange technology.

Conventional canning has long been known to result in a significant destruction of valuable nutrients and a loss of overall quality of the food product, especially in the processing of highly viscous fluid foods and foods containing particulates. Aseptic processing has been claimed to potentially deliver higher quality food products under continuous flow, however, this has worked principally for liquids. Sastry & Cornelius (2002) reviewed the challenges associated with continuous aseptic processing of particulate foods by conventional heat exchange methods, which rely the liquid phase to transfer heat to the solid phase. Even if the interfacial convective heat transfer is high, the rate of heating at the cold spots within the particle might be limited by the rate of thermal conduction within the suspended particle itself (Fryer et al., 1993). Additionally, the rate
of thermal conduction within the solids phase limits the size of the particulates that can be processed by this conventional technique (de Ruyter & Brunet, 1973).

Ohmic heating offers an attractive alternative because it simultaneously heats both phases by internal energy generation, and has potential applications for processing such food products (Palaniappan & Sastry, 2002). For any food product that is commercially sterilized in the United States, the FDA requires that the sterilization process be filed with them. A process filing is a document which describes details of the sterilization process (such as mathematical models, experimental data, microbiological verification data, etc) which shows that the processor fully understands the sterilization process and is completely aware of the worst case scenario (Larkin & Spinak, 1996). The identification, control and validation of all the critical control points required to demonstrate that an ohmically processed multiphase low acid food product has been rendered commercially sterile is more difficult than that for conventional methods. A base of knowledge needs to be developed before ohmic heating can be commercially used. This research project aims to provide the first steps towards preparation of a model process filing for ohmic heating, such that, in future any processor interested in ohmic heating can use this model process filing protocol as a reference for his/her own process.

Ohmic heating involves the application of a cyclical potential to a material, resulting in heat generation due to ionic motion. The basic relationship for the energy generation rate is:

\[ \dot{u} = \sigma |\nabla V|^2 \]  

(1.1)

The critical property affecting energy generation is the electrical conductivity (\(\sigma\)) of the material. Palaniappan & Sastry (1991), and Mitchell & de Alwis (1989) measured
electrical conductivities of some solid foods. Ruhlman et al. (2001) reported electrical conductivities of some liquid foods at different temperatures. For particulate foods it has been observed that most vegetables and meats have lower electrical conductivities than liquid foods components (Tulsiyan et al. 2007a).

In an ohmic heating process for particulate foods, the most desirable situation is that in which the electrical conductivities of fluid and solid particles are equal (Wang & Sastry, 1993a), thus close matching of electrical conductivities between phases would be highly desirable. Wang & Sastry (1993a, b), showed that it is possible to increase the electrolytic content within foodstuffs, and raise electrical conductivity by salt infusion. This effect may be accomplished via the relatively slow soaking or marination process or the more rapid blanching process in salt solution. However, it is also necessary that the composition and other properties of the food are not greatly affected. By adjusting the electrical properties of different solid components it may become possible to heat solids at similar rate or even faster than the sauce.

Diffusion of salt in solid foods such as pork, beef and fish has been studied by many researchers (Wistreich, Morse & Kenyon, 1960; Wood, 1966; Del Valle & Nickerson, 1967a,b; Dussap & Gros, 1980). Liu (1992), Drusas & Vagenas (1988), and Wang & Sastry (1993b) determined salt diffusivity in vegetable tissues.

As with any continuous flow process, in-situ temperature monitoring remains a challenge, hence, adequate mathematical models as well as experimental verification are critical. Modeling and experimental studies to identify the worst-case heating scenario during ohmic processing of particulate foods were carried out by deAlwis & Fryer (1990), Sastry (1992), Sastry & Palaniappan (1992b,c), Fryer et al. (1993), Zhang &
Fryer (1993), Khalaf & Sastry (1996), Orangi et al. (1998), Sastry & Salengke (1998), and Sensoy (2002). Under static ohmic heating conditions particle-liquid mixture heat at rates depending on relative conductivities of the phases and the volume fractions of the respective phases (Sastry & Palaniappan, 1992c). Solids of low conductivity compared to the liquid will lag thermally if they are in low concentration, but under high-concentration conditions, particles may heat faster than fluid. This occurs because as solids content increases, current paths through the fluid become more tortuous, forcing a greater proportion of the total current to flow through the particles. This can result in higher energy generation rates within the particles and consequently a greater relative particle heating rate. Sastry (1992) further modified the model to predict temperatures of fluids and particles within a continuous ohmic heater. It was observed that if a particle of low conductivity is surrounded by a high-conductivity environment, this particle will thermally lag the fluid. If isolated low-conductivity particles enter the system, the danger of under processing exists. From the safety point of view, it is important to determine the worst-case scenario, and this is most likely associated with undetected low-conductivity particles in the system.

The most critical factors to be fully measured and determined in a continuous sterilization process can be classified into the temperature of the coldest spot and the shortest residence times spent in the heating and holding system. Residence Time Distribution (RTD) measurement is needed because of the difficulty in noninvasive measurement of the particle internal temperatures during continuous flow (Sastry & Cornelius 2002). Residence time of the fastest-moving particle is necessary for designing
a process via mathematical modeling to ensure commercial sterility, and for biological validation of the model.

The RTD experiment must be able to demonstrate with a high degree of confidence that the fastest particle has indeed been sampled and therefore the sample size becomes critical. DiGeronimo et al. (1997) stated that a distribution-free method was the most appropriate method to determine reliably the characteristic fastest particle of the system. The following equation was used to calculate the number of data points needed for given $P$ and $C$ values (Palaniappan & Sizer 1997):

$$N = \frac{\log(1 - C)}{\log(1 - P)}$$  \hspace{1cm} (1.2)

For $C = 0.95$ and a $P$ value of 0.01, a population size of 299 particles is necessary.

Ramaswamy et al. (1995), Sastry (1997) and Sastry & Cornelius (2002) reviewed several techniques developed for studying and investigating the RTD of solid-liquid flow. A popular technique with the industry is the use of magnetic methods which involve introduction of tagged particles containing small magnets (Chandarana & Unverferth 1996; Segner et al., 1989). Their principal limitation, however, is the inability to distinguish between multiple particles passing through the detector at the same time. This necessitates that operator wait for each magnetic tracer to enter and exit the system before introduction of the next tracer (Sastry & Cornelius 2002). Radio Frequency Identification (RFID) technology allows tracking of multiple particles inside the system, thus obviating the waiting time needed in magnetic method (Tulsiyan, et al., 2007b). RTD of food particles inside ohmic heaters depends on system variables like system dimensions, orientation, rotational speed of the agitators, and product flow rate; particle variables like
concentration, shape, size, type, and density; and the fluid viscosity. There is a need to study, in detail, the effect of these variables on the RTD in the ohmic heaters.

1.1 Nomenclature

\( C \) confidence of collecting the “fastest” particle fraction

\( N \) population size

\( P \) “fastest” particle fraction

\( V \) voltage across the sample (V)

\( \dot{u} \) specific internal energy generation rate (W/m\(^3\))

\( \sigma \) electrical conductivity (S/m)

1.2 References


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CHAPTER 2

ELECTRICAL CONDUCTIVITY OF FRUITS AND MEATS DURING OHMIC HEATING

2.1 Abstract

The design of effective ohmic heaters depends on the electrical conductivity of foods. Electrical conductivities of six different fresh fruits (red apple, golden apple, peach, pear, pineapple and strawberry) and several different cuts of three types of meat (chicken, pork and beef) were determined from room temperature through the sterilization temperature range (25 -140°C). In all cases, conductivities increased linearly with temperature. In general, fruits were less conductive than meat samples. Within fruits; peach and strawberry were more conductive than apples, pear, and pineapple. Conductivity measurements of meat cuts showed that lean is much more conductive compared to fat. Fat content of all lean muscle cuts was measured and no strong relationship could be observed between the electrical conductivity and the lean muscle fat content.
2.2 Introduction

In ohmic or electroconductive heating, foods are heated by passing alternating current through them. 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 & Sastry, 1991). A large number of potential applications exist for ohmic heating, including blanching, evaporation, dehydration, fermentation, and extraction. In case of the application as heat treatment for microbial control ohmic heating provides rapid and uniform heating, resulting in less thermal damage to the product. A high-quality product with minimal structural, nutritional, or organoleptic changes can be manufactured in a short operating time (Rahman, 1999). Ohmic heating is currently being used for the processing of whole fruits, syroped fruit-salad and fruit juices in Japan and the United Kingdom. Ohmic heating has shown to enhance drying rates (Lima & Sastry, 1999; Wang & Sastry, 2000; Zhong & Lima, 2003) and extraction yields (Lima & Sastry, 1999; Wang & Sastry, 2002; Halden, de Alwis & Fryer, 1990) in certain fruits and vegetables.

The rate of heating is directly proportional to the electrical conductivity and the square of the electric field strength (Sastry & Palaniappan, 1992). Palaniappan and Sastry (1991) reported that electrical conductivity is a linear function of temperature, and the relationship can be expressed as:

\[ \sigma_T = \sigma_{ref} \left[ 1 + m \left( T - T_{ref} \right) \right] \]  

(2.1)

Much research has been done on the electrical conductivity of liquid fruit products like juices and purees (Palaniappan & Sastry, 1991; Icier & Ilcali, 2005; Castro, Teixeira, Salengke, Sastry & Vicente, 2004). Mitchell & de Alwis (1989) measured electrical

Electrical properties of meat have also been investigated in recent years (Saif, Lan, Wang & Garcia, 2004). Conductivities of chicken (Mitchell & de Alwis, 1989; Palaniappan & Sastry, 1991) beef (Kim, Kim, Park, Cho & Han, 1996; Palaniappan & Sastry, 1991) and pork (Halden, de Alwis, & Fryer, 1990) have been measured, but the type of meat cut was not specified. Tulsiyan, Sarang & Sastry (2007) measured conductivity of chicken breast over the sterilization temperature range. Shirsat, Lyng, Brunton & McKenna (2004) reported conductivities of different pork cuts and observed that lean is highly conductive compared to fat, however, conductivity measurements were performed only at 20°C.

The aim of this study was to measure electrical conductivity of selected fresh fruits (red apple, golden apple, peach, pear, pineapple and strawberry) and different cuts of fresh meat (chicken, pork and beef) over the sterilization temperature range during ohmic heating.

2.3 Materials and methods

Listed in Table 2.1, are the several fruits and meat cuts that were studied. Meat cuts were selected to cover different parts of the animal, and to represent various fat contents (USDA Handbook 8, 2005). Samples were procured from local grocery store (Giant Eagle, Columbus, OH) and refrigerated until used. Except for the case of chicken
fat, all meat cuts were trimmed to separate lean from fat to ensure that only the conductivity of lean was measured.

2.3.1 Electrical conductivity

2.3.1.1 Experimental device

The setup, explained in detail elsewhere (Tulsiyan, Sarang & Sastry, 2007), consisted of ten cylindrical ohmic heating chambers equipped with platinized titanium electrodes. The device was pressurized, and allowed measurement of the electrical conductivity of ten samples at a time and at temperatures up to $140^\circ C$. A schematic diagram of the electrical circuitry is shown in Fig. 2.1. Samples were clamped at the ends by two electrodes in each cell, and a T-type copper-constantan, Teflon coated thermocouple (Cleveland Electric Laboratories, Twinsburg, OH) with compression fitting was used to measure the temperature at the geometric center of the sample. The ohmic cells were connected to a relay switch which directed the order in which the cells were heated. Voltage and current transducers were used to measure the voltage across the samples and the current flowing through them. A data logger (Campbell Scientific Inc., Logan, UT) was used to record data at constant time intervals.

2.3.1.2 Methodology

Cylindrical samples of fruits and meat (ten samples each) were prepared using a slicer and a set of cork borers. The samples were 0.0079m (0.313”) in length and 0.0078m (0.308”) in diameter. Samples may shrink and loose contact with the electrodes when ohmically heated to higher temperatures, hence, samples of the same diameter but fractionally longer compared to the sample chamber were prepared and sandwiched
between the electrodes. All the meat samples were cut perpendicular to the muscle fibers, so that the muscle fibers would be perpendicular to the electric field. A thermocouple was then inserted into the cell through the thermocouple port and each sample was heated to 140°C using alternating current of 60 Hz and voltage between 15 to 20V. The temperature, voltage and current were measured continuously and recorded using the data logger linked to the computer. It was difficult to get cylindrical sample of the meat separable fat of required dimensions, and the conductivities were measured by packing as much as fat possible in the sample chamber.

2.3.1.3 Analysis

The electrical conductivity of the samples was calculated using the dimensions of the cell, voltage and the current, using the formula:

$$\sigma = \frac{LI}{AV} \quad (2.2)$$

2.3.1.4 Error estimation

The accuracy of each electrode set was tested, before and after the experiments, by determining the electrical conductivity of three different calibration salt solutions (conductivity standard solution 8974 μS/cm, 12880 μS/cm & 15000 μS/cm, OAKTON Instruments, Vernon Hills, IL, USA). The maximum difference between the measured and the reference value for any heating cell was 9%. The temperature at the center of the sample was used as the representative value, and was assumed to be spatially uniform because of the small size of the sample.
2.3.2 Fat analysis of meat

Fat and moisture content of the meat was determined using HFT 2000f DSC (Data Support Company Inc., Encino, CA) fat and moisture analyzer (accuracy is ± 0.5% range of 1%). Fat and moisture content was measured for three replicate runs for each sample. For each replicate, first 50 grams of sample was fine ground using Mincer/Chopper HC 20 (Black & Decker Inc., Shelton, CT) and 3-4 grams of sample was then used for analysis.

2.4 Results and discussion

Electrical conductivity-temperature curves for selected fresh fruits, and different cuts of chicken, pork and beef are shown in Fig. 2.2, through Fig. 2.5, respectively. Y-error bars shown are single standard deviations. The conductivity data is also summarized for selected temperatures in Table 2.2, through Table 2.5. The conductivity data was subjected to analysis of variance (ANOVA) and mean values in the same row with the same letter are not significantly different (p>0.05 for $\alpha = 0.05$). For all samples, electrical conductivity increased almost linearly with temperature, as is expected and consistent with literature data (Palaniappan & Sastry, 1991; Castro, et al., 2003; Tulsiyan, Sarang & Sastry, 2007). The linear model (equation 2.1) by Palaniappan & Sastry (1991) was used to fit the electrical conductivity data of fruit and meat samples. $m$, $\sigma_{ref}$ and $R^2$ values are shown in Table 2.6. High coefficients of determination ($R^2>0.97$) indicate the suitability of the linear model for conductivity variation with temperature for all the samples tested.

From Table 2.2 it can be observed that the electrical conductivities of red apple and golden apple were not significantly different over the temperature range studied, and
hereafter mentioned together as apples. At 25°C the electrical conductivity of pineapple was very low and significantly different than apples and pear. Electrical conductivity of peach and strawberry was high and not significantly different compared to each other, while significantly different compared to other fruits. At higher temperatures (40-140°C), apples and pineapple had low conductivity. Conductivity of pear was high compared to apples and pineapple and significantly different compared to all other fruits. Strawberry and peach had higher conductivity and significantly different compared to other fruits. The gap in the electrical conductivity between strawberry and peach, and other fruits increased with the temperature. Mavroudis et al. (2004) and Rahman et al. (2005) measured porosity of fresh apples and observed that the porosity can be as high as 20%. The presence of large amount of air might explain low conductivity of apple tissues. Mitchell & de Alwis (1989) reported conductivity of pear (0.041 S/m) and apple (0.023 S/m) at 25°C. From Table 2.2, it can be observed that the conductivity at 25°C of pear is 0.084 S/m, red apple is 0.075 S/m and of golden apple is 0.067 S/m. Mitchell & de Alwis (1989) measured conductivity at 50 Hz while we used 60 Hz supply, which might explain the difference in the measured electrical conductivity of pear and apple samples. Castro, et al. (2003) measured electrical conductivity of fresh strawberries at different field strengths. At 25 V/cm they reported conductivity to be approximately 0.05 S/m at 25°C and 0.55 S/m at 100°C, and it increased linearly. From Table 2.2, it can be observed that conductivity of strawberry increased from 0.186 S/m at 25°C to about 0.982 S/m at 100°C. Again these researchers measured conductivity using 50 Hz power supply and higher field strength. Difference in the power source and the natural variation among the species might explain the difference in the electrical conductivities observed.
Fig. 2.3 shows conductivity of different cuts of chicken and the data is summarized in Table 2.3. It can be observed that separable fat is the least conductive. At all temperatures lean chicken breast is most conductive and that the conductivities of different cuts are significantly different from each other. It was difficult to obtain conductivity data for chicken separable fat at higher temperatures without spoiling (damaging the coating) the electrodes. Thus, conductivity was measured only till 135°C. Also, to preserve the electrodes, conductivity of pork and beef separable fat was not determined. It may be safely assumed that separable fat will be significantly lower in conductivity compared to lean muscle cuts. Fat and moisture content (percent by weight) of chicken cuts were measured and are summarized in Table 2.7. In Fig 2.6, electrical conductivity of chicken muscle cuts are plotted against their average fat content at 25°C and at 140°C. It may be observed that electrical conductivity reduced with increase in the total fat content. However, it can also be observed that chicken breast contains more fat but still is more conductive than tenders and drumstick.

Electrical conductivity variation with temperature of three different cuts of lean pork muscles is shown in Fig. 2.4 and the data is summarized in Table 2.4. At higher temperatures (above 100°C) tenderloin is more conductive than loin and shoulder. Measured fat content of pork cuts are shown in Table 2.7. Top loin contains more fat compared to shoulder and tenderloin, however the conductivity data (Table 2.4) shows that tenderloin is more conductive than top loin and shoulder. For pork cuts no particular trend could be observed between the conductivity and the total fat content. Shirsat, et al. (2004) measured electrical conductivity of fresh pork cuts of leg (topside), shoulder (picnic), and back and belly fat. They reported that lean is highly conductive compared
to fat. They also observed that the conductivity of leg (fat content 0.4%) and shoulder (fat content 0.9%) was significantly different, but conductivity of shoulder and belly (fat content 2.3%) was not significantly different. They concluded that in addition to the fat content the structural differences may influence the conductivity of muscles.

Fig. 2.5 shows conductivity of different lean cuts of beef and the data is summarized in Table 2.5. At lower temperatures (up to 60°C) flank loin had lowest conductivity and significantly different compared to other muscle cuts, while at higher temperatures the conductivities of all cuts were almost similar. Beef cuts showed considerable variation and were not significantly different in terms of the measured fat content (see Table 2.7).

Increase in the electrical conductivity during heating of the biological tissue occurs due to increase in the ionic mobility because of structural changes in the tissue like cell wall protopectin breakdown, expulsion of non conductive gas bubbles, softening, and lowering in aqueous phase viscosity (Bean, Rasor & Porter, 1960; Sasson & Monselise, 1977). Higher electrical conductivity of strawberry and peach may be attributed to the softer tissues and hence higher ionic mobility in comparison to the harder tissues of apples, pineapple and pear. Also, as mentioned earlier, presence of large amount of air might result in lower electrical conductivity of apple tissues. The other most important factor influencing the conductivity is the total ionic content of these fruits. Measurement of the total ionic content - sugars and salts - and comparison of the conductivity based on the ionic contents is a topic for future study. In meat, the separable fat has significantly lower conductivity compared to lean muscle cuts. In Fig.2.7, electrical conductivities of the lean muscle cuts at 25°C and at 140°C are plotted against
their fat content (mean values). Linear regression analysis gave $R^2 = 0.038$ at 25°C, and 0.050 at 140°C. Thus, within the lean muscle cuts it is difficult to find any relationship between the electrical conductivity and measured muscle fat content. Salengke & Sastry (2007a,b) and Sastry & Palaniappan (1992) performed mathematical modeling and experimental investigation of the case where less conductive particle is surrounded by high conductive medium and heated ohmically under static condition. They observed that the current channels through a more conductive medium and may bypass the less conductive particle. Also, the presence or absence of the alternative conducting paths through the surrounding medium is an important factor affecting voltage drops and consequently, energy generation rates within both media. Similar explanation might be offered when a low conductive fat is surrounded by high conductive muscle tissues. In addition to the conductivity difference, the size and the distribution of the non conductive fat in the muscle tissues might play an important role. In summary, for lean muscle cuts marbling (fat distribution) may be an important factor affecting the electrical conductivity; which needs further investigation.

2.5 Conclusions

The electrical conductivity of various fruits and meats increased linearly with the temperature during ohmic heating at constant voltage gradient. Lower electrical conductivity may be observed for highly porous materials like apples. There was no strong relationship between the measured fat content of the lean muscle cuts and their electrical conductivity. Fat distribution or marbling might be an important factor affecting the electrical conductivity of meat.
2.6 Nomenclature

- $A$: cross sectional area of the sample ($m^2$)
- $I$: current flowing through the sample (A)
- $L$: length of the sample (m)
- $m$: temperature compensation constant
- $T$: temperature (°C)
- $T_{\text{ref}}$: reference temperature (°C)
- $V$: voltage across the sample (V)
- $\sigma$: electrical conductivity (S/m)
- $\sigma_{\text{ref}}$: electrical conductivity at reference temperature (S/m)
- $\sigma_T$: electrical conductivity at any temperature (S/m)

2.7 References


Figure 2.1- Schematic diagram of the experimental setup for electrical conductivity measurements.
Figure 2.2- Electrical conductivity of fruits (1 std. dev.)
Figure 2.3- Electrical conductivity of different cuts of chicken (1 std. dev.)
Figure 2.4- Electrical conductivity of different pork cuts (1 std. dev.)
Figure 2.5- Electrical conductivity of different beef cuts (1 std. dev.)
Figure 2.6 - Effect of fat content on the electrical conductivity of chicken cuts at 25°C and 140°C.
Figure 2.7 - Effect of fat content on the electrical conductivity of lean muscle cuts at 25°C and 140°C.
### 2.9 Tables

<table>
<thead>
<tr>
<th>Fruits</th>
<th>Apple (Red Delicious), Apple (Golden Delicious), Strawberry (Dole Fresh Picked), Pear and Pineapple (Dole Tropical Gold).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicken (USDA Grade A)</td>
<td>Breast, drumstick, tender, and thigh.</td>
</tr>
<tr>
<td>Pork</td>
<td>Top loin, shoulder (boston butt roast) and tenderloin.</td>
</tr>
<tr>
<td>Beef (USDA Choice Grade)</td>
<td>Chuck shoulder, flank loin, round bottom round and round top round.</td>
</tr>
</tbody>
</table>

**Table 2.1** – Fruits and meat cuts selected for electrical conductivity measurements.
### Table 2.2 – The Electrical conductivity (S/m) of fruit samples measured at various temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Apple – green</th>
<th>Apple – red</th>
<th>Peach</th>
<th>Pear</th>
<th>Pineapple</th>
<th>Strawberry</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.067±0.020&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.075±0.016&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.170±0.018&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.084±0.019&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.037±0.014&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.186±0.047&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>40</td>
<td>0.144±0.024&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.138±0.011&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.307±0.022&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.173±0.009&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.141±0.034&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.335±0.060&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>60</td>
<td>0.251±0.042&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.239±0.031&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.541±0.043&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.313±0.059&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.245±0.052&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.592±0.108&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>80</td>
<td>0.352±0.049&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.339±0.047&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.738±0.064&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.439±0.082&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.348±0.067&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.801±0.148&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>100</td>
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<td>0.419±0.053&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.941±0.092&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.541±0.098&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.432±0.070&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.982±0.176&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>120</td>
<td>0.504±0.059&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.499±0.052&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.123±0.130&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.607±0.080&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.506±0.080&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.143±0.178&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>140</td>
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<td>0.642±0.088&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.575±0.081&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.276±0.180&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

* Average of 10 sample values (± std. dev.)

Mean values in the same row with the same letter are not significantly different (p>0.05 for α = 0.05)
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Breast</th>
<th>Tender</th>
<th>Thigh</th>
<th>Drumstick</th>
<th>Separable fat</th>
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<tbody>
<tr>
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<td>0.549±0.023&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.348±0.040&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>0.672±0.068&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.598±0.056&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.057±0.018&lt;sup&gt;d&lt;/sup&gt;</td>
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<td>1.601±0.133&lt;sup&gt;d&lt;/sup&gt;</td>
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</table>

* Average of 10 sample values (± std. dev.)

Mean values in the same row with the same letter are not significantly different (p>0.05 for α = 0.05)

**Table 2.3** – The Electrical conductivity (S/m)* of chicken samples measured at various temperatures.
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Loin</th>
<th>Shoulder</th>
<th>Tenderloin</th>
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<tbody>
<tr>
<td>25</td>
<td>0.560±0.051^a,b</td>
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<tr>
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<td>1.961±0.072^b</td>
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* Average of 10 sample values (± std. dev.)

Mean values in the same row with the same letter are not significantly different (p>0.05 for α = 0.05)

**Table 2.4** – The Electrical conductivity (S/m)* of pork samples measured at various temperatures.
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Bottom round</th>
<th>Chuck shoulder</th>
<th>Flank loin</th>
<th>Top round</th>
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<tr>
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<td>0.626±0.085\textsuperscript{a}</td>
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<td>0.801±0.113\textsuperscript{a}</td>
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<td>0.841±0.051\textsuperscript{a}</td>
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<td>80</td>
<td>1.037±0.084\textsuperscript{a,b}</td>
<td>1.019±0.156\textsuperscript{a,b}</td>
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<tr>
<td>140</td>
<td>1.608±0.139\textsuperscript{a}</td>
<td>1.665±0.279\textsuperscript{a}</td>
<td>1.696±0.250\textsuperscript{a}</td>
<td>1.721±0.128\textsuperscript{a}</td>
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* Average of 10 sample values (± std. dev.)

Mean values in the same row with the same letter are not significantly different (p>0.05 for $\alpha = 0.05$)

**Table 2.5** – The Electrical conductivity (S/m)* of beef samples measured at various temperatures.
<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\text{ref}}$ (S/m)</th>
<th>$m$ ($^\circ$C$^{-1}$)</th>
<th>$R^2$</th>
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<tbody>
<tr>
<td><strong>Fruits</strong></td>
<td></td>
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<td>Apple-golden</td>
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<td>Apple-red</td>
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<td>0.179</td>
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<td>0.99</td>
</tr>
<tr>
<td>Strawberry</td>
<td>0.234</td>
<td>0.041</td>
<td>0.99</td>
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<tr>
<td>Breast</td>
<td>0.663</td>
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<td>0.99</td>
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<tr>
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<td>0.99</td>
</tr>
<tr>
<td>Thigh</td>
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<td>0.026</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Tenderloin</td>
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<tr>
<td><strong>Beef</strong></td>
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<td></td>
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<tr>
<td>Bottom round</td>
<td>0.504</td>
<td>0.019</td>
<td>0.99</td>
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<tr>
<td>Chuck shoulder</td>
<td>0.456</td>
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<td>0.99</td>
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<td>Flank loin</td>
<td>0.318</td>
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<td>0.472</td>
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Table 2.6 – Electrical conductivity-temperature model parameters
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<tr>
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<td>%</td>
<td>%</td>
</tr>
<tr>
<td><strong>Chicken</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Breast</td>
<td>75.33±0.40&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.63±0.52&lt;sup&gt;a,b&lt;/sup&gt;</td>
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<tr>
<td>Tender</td>
<td>76.36±0.08&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.32±0.10&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Drumstick</td>
<td>76.75±0.50&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.67±0.22&lt;sup&gt;a,b&lt;/sup&gt;</td>
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<tr>
<td>Thigh</td>
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<td>2.90±0.46&lt;sup&gt;b&lt;/sup&gt;</td>
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<td>Separable fat</td>
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<tr>
<td><strong>Pork</strong></td>
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<tr>
<td>Shoulder</td>
<td>75.74±0.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.38±0.06&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>Tenderloin</td>
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<td>3.52±0.35&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Loin</td>
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<td>7.39±0.43&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>Separable fat</td>
<td>15.53±0.49&lt;sup&gt;c&lt;/sup&gt;</td>
<td>79.31±1.44&lt;sup&gt;c&lt;/sup&gt;</td>
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<tr>
<td><strong>Beef</strong></td>
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<tr>
<td>Top round</td>
<td>73.32±0.79&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.30±1.02&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Chuck shoulder</td>
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<td>7.04±1.15&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Flank loin</td>
<td>71.76±0.61&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.19±0.78&lt;sup&gt;a&lt;/sup&gt;</td>
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<tr>
<td>Bottom round</td>
<td>72.79±1.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.87±1.52&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Separable fat</td>
<td>11.39±2.56&lt;sup&gt;b&lt;/sup&gt;</td>
<td>83.54±2.62&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

* Average of three replicates (± std. dev.)

Mean values in the same column with same letter are not significantly different (p>0.05 for α = 0.05), considered separately for chicken, pork and beef.

**Table 2.7** – Moisture and fat content* of meat cuts
CHAPTER 3

BLANCHING AS A PRETREATMENT METHOD TO IMPROVE UNIFORMITY IN HEATING OF SOLID-LIQUID FOOD MIXTURES

3.1 Abstract

The electrical conductivity of food components is critical to ohmic heating. Food components of different electrical conductivities heat at different rates. While equal electrical conductivities of all phases is desirable, real food products may behave differently. In the present study involving chicken chowmein consisting of a sauce and different solid components; celery, water chestnuts, mushrooms, bean sprouts and chicken; it was observed that the sauce was more conductive than all solid components over the measured temperature range. To improve heating uniformity, a blanching method was developed to increase the ionic content of the solid components. By blanching different solid components in a highly conductive sauce at 100 °C for different lengths of time, it was possible to adjust their conductivity to that of the sauce. Chicken chowmein samples containing blanched particulates were compared with untreated samples with respect to ohmic heating uniformity at 60-Hz up to 140°C. All components of the treated product containing blanched solids heated more uniformly than untreated product. In sensory tests, three different formulations of the blanched product showed
good quality attributes and overall acceptability, demonstrating the practical feasibility of the blanching protocol.

### 3.2 Introduction

Ohmic heating may be used to heat food internally by passing an electric current through it. This, in principle, reduces thermal abuse to the product, in comparison to conventional heating, where slow heat penetration may occur (Sastry & Li, 1996). Thus, ohmic heating has potential for continuous sterilization of low-acid food containing particulates (Palaniappan & Sastry, 2002).

The rate of heating is directly proportional to the electrical conductivity and the square of the electric field strength (Sastry & Palaniappan, 1992). Thus, electrical conductivity is the critical food property, determined as:

$$\sigma = \frac{LI}{AV}$$  \hspace{1cm} (3.1)

Since the electrical conductivity of most foods increases with temperature, ohmic heating becomes more effective as the temperature increases (Sastry & Palaniappan, 1992).

Palaniappan and Sastry (1991), and Mitchell and de Alwis (1989) measured electrical conductivities of some solid foods. Ruhlman et al. (2001) reported electrical conductivities of some liquid foods at different temperatures. For particulate foods it has been observed that most vegetables and meats have lower electrical conductivities than liquids (Tulsiyan, Sarang & Sastry, 2007). In an ohmic heating process for particulate foods, the most desirable situation is that in which the electrical conductivities of fluid and solid particles are equal (Wang & Sastry, 1993a).
Sastry and Palaniappan (1992) performed mathematical modeling and experimental studies to determine heating rates of a liquid-particle mixture in a static ohmic heater. They observed that particle-liquid mixture heat at rates depending on relative conductivities of the phases and the volume fractions of the respective phases. Solids of low conductivity compared to liquid will lag behind if they are in low concentration, but under high-concentration conditions, particles may heat faster than fluid. This occurs because as solids content increases, current paths through the fluid become more tortuous, forcing a greater proportion of the total current to flow through the particles. This can result in higher energy generation rates within the particles and consequently a greater relative particle heating rate. Sastry (1992) further modified the model to predict temperatures of fluids and particles within a continuous ohmic heater. It was observed that if a particle of low conductivity is surrounded by a high-conductivity environment, this particle will thermally lag the fluid. If isolated low-conductivity particles enter the system, the danger of under processing exists. From the safety point of view, it is important to determine the worst-case scenario, and this is most likely associated with undetected low-conductivity particles in the system. By increasing the electrolytic content in the solids, such low-conductivity particles may be made to heat at similar rate or faster than the surrounding fluid.

Increase in the electrolytic content within foods to increase electrical conductivity may be accomplished by salt infusion via soaking or blanching of solids in salt solution. This may be used as a pretreatment for ohmic heating for particulate foods to obtain uniform heat treatment, if the composition and other properties of the food are not greatly affected. The conductivities of vegetable samples could be increased by soaking them in
salt solutions (Palaniappan & Sastry, 1991; Wang & Sastry, 1993a and 1993b). Relationship between the salt concentration profile and the electrical conductivity were also determined. However, a low-temperature soaking method has the disadvantage of being time consuming.

The current work has the larger objective of development of safe processing protocols for chicken chowmein, a low-acid particulate food, currently a menu item in military rations. The formulation is shown in Table 3.1. Chowmein sauce composition is as shown in Table 3.2. Tulsiyan, Sarang and Sastry (2007) measured the electrical conductivities of the individual components of the chicken chowmein over the process sterilization temperature range. Results showed that the sauce (2.1 S/m at 27°C to 6.8 S/m at 140°C) was much more conductive than the solid components, i.e., celery (0.1 S/m to 3.4 S/m), water chestnut (0.1 S/m to 2.8 S/m), mushrooms (0.2 S/m to 1.4 S/m), bean sprouts (0.2 S/m to 1.5 S/m) and chicken (0.6 S/m to 3.4 S/m). Variation in electrical conductivity-temperature plots was also observed between different samples of the same component. The reason for the high electrical conductivity of the chowmein sauce was determined to be the salt and highly conductive soy sauce present in it. The results suggest that if a sterilization process based on ohmic heating is to be successful, the formulation needs to be modified so that the components approach a nearly isoconductive state. This may be done by treatment of the solid phase via salt infusion.

On adjusting the electrical properties of different components it may be possible to ensure that uniform heating of the product takes place. However, it is necessary to determine that composition and other properties of the food are not greatly affected. Sensory tests should be carried out whenever necessary and adjustments in the
The objectives of this research were to; (1) develop a blanching method for increasing the ionic content in solid particulates and adjusting the electrical conductivities of the solid components to that of sauce, (2) under static ohmic heating conditions, determine the heating rate of solid and liquid components in product containing pretreated solids, and compare it with heating rates of components in the untreated product, and (3) conduct sensory tests to ensure that the infusion process results in a desirable end product.

3.3 Materials and methods

Chicken chowmein formulation is as shown in Table 3.1 and Table 3.2. Frozen 0.01875 m (0.75 in.) cubic chicken pieces of boneless skinless chicken from the breast portion, fresh bean sprouts (cylindrical; approximate diameter 4 mm and length between 40-70 mm), cut celery (12.7 mm; 0.5 in.), sliced white button mushrooms (12.7 mm; 0.5 in.) and canned sliced water chestnuts were used. Other ingredients were chicken fat (North Market, Columbus, OH), food starch (Purity Cloud® Modified Food Starch, National Starch & Chemicals, NJ), soy sauce (Kikkoman Foods Inc., San Francisco, CA), dehydrated onions, white granulated sugar and white ground pepper (Kroger, Columbus, OH).

There were three parts to this study; (i) blanching chicken and vegetables in highly conductive soy sauce at 100 °C for different lengths of time to adjust their
electrical conductivity to that of sauce, (ii) determination of the heating rates of different components in the product with blanched solids and with untreated solids under a batch ohmic heating condition, and (iii) conducting sensory tests and adjusting the formulation if necessary.

3.3.1 Determination of electrical conductivity

The setup consisted of ten cylindrical ohmic heating chambers, equipped with platinized titanium electrodes explained in detail elsewhere (Tulsiyan, Sarang and Sastry 2007). The device was pressurized, and allowed measurement of the electrical conductivity of ten samples at a time and at temperatures up to 140°C. A schematic diagram of the electrical circuitry is shown in Figure 3.1. Samples were clamped at the ends by two electrodes in each cell, and a T-type copper-constantan, Teflon coated thermocouple (Cleveland Electric Laboratories, Twinsburg, OH) with compression fitting was used to measure the temperature at the geometric center of the sample. The ohmic cells were connected to a relay switch which directed the order in which the cells were heated. Voltage and current transducers were used to measure the voltage across the samples and the current flowing through them. A data logger (Campbell Scientific Inc, Logan, UT) linked to a computer was used to obtain the voltage, current and temperature data at constant time intervals. The electrical conductivity can be calculated using Eq. 1, based on the cell dimensions, and the voltage and current data.

3.3.2 Blanching

Diced chicken and cut vegetables as used in the product were blanched in sauce (blanching sauce formulation is as shown in Table 3.3) at 100°C for different lengths of
time. Sauce formulation for blanching was decided based on our preliminary (trial-and-error) experimental results. The samples were then taken out and electrical conductivity determined over a range of temperatures to 140°C, using the procedure described above. Three replicate experiments were conducted. Electrical conductivities of the blanched chicken and vegetables, over the entire temperature range, were compared with that of the sauce. In deciding on the optimal blanch times, we chose the minimum time required for a component to reach the desired electrical conductivity. In some cases (as with chicken) this end point was never achieved. Since even longer treatment times would only result in marginal electrical conductivity gains, while degrading the product, we were content with the maximum blanch time that was studied.

### 3.3.3 Ohmic heating and determination of heating rates

Based on the blanching time determined in the previous step, a protocol was developed for preparing chicken chowmein while maintaining a final formulation similar to that mentioned in Table 3.1 and Table 3.2. The flow chart with the preparation steps is shown in Figure 3.2. The chowmein sauce was prepared separately by adding water, chicken fat, starch and onions to the blanching sauce (sauce left after blanching chicken and vegetables) in the proportion mentioned in Table 3.4. The sauce was heated till it formed a brown thick paste. Starch gelatinization was observed at around 70°C. Blanched chicken and vegetables were added to the sauce in the proportion mentioned in Table 3.1, to make the final product, which was then cooled to room temperature.

The whole product was heated in a 2 in. diameter ohmic cell keeping the rest of the experimental setup similar (Figure 3.1). One thermocouple was inserted in each component of the product and the temperature was monitored. The ohmic heating cell
was pressurized so that the product could be heated up to sterilization temperature. The current, voltage and temperature of each component were recorded by the data-logger every 1 s during the heating process. Three replicate experiments were conducted. Heating rates of different components in the product were obtained and compared.

Another chicken chowmein product was prepared using untreated chicken and vegetables. The ohmic heating procedure was repeated as explained before. Heating rates of different components in the product were measured and compared.

3.3.4 Sensory evaluation

Sensory evaluations are necessary to ensure that the blanching protocol results in high-quality end product. Chicken chowmein samples were prepared following the protocol of Figure 3.2, and tested by a sensory panel at the US Army Natick Soldier Center. To avoid repeated trial-and-error optimization of the formulation, we chose to simultaneously test three alternative formulations, intending to select only from those that were acceptable to panels. The three products were; (1) original formulation, Table 3.1, (2) fresh onions instead of dehydrated onions, and (3) brown sugar instead of white granulated sugar and fresh onions instead of dehydrated onions. Three different formulations of conductivity adjusted product were evaluated for their appearance, odor, flavor, texture and overall quality, and rated on a nine-point hedonic scale (1 = dislike extremely and 9 = like extremely).
3.4 Results and discussion

Pieces of each component were blanched at boiling temperature in blanching sauce for different lengths of time. Figures 3.3-3.7 shows the conductivity variations for these blanched solids (bean sprouts, celery, chicken, mushroom and water chestnut) for different blanching times (error bars showing single standard deviation). Increasing the blanching time increases the ionic content of the solids and hence the electrical conductivity. As vegetable tissue is heated, structural changes like cell wall breakdown, tissue damage, increase of mobile moisture and softening occurs, affecting the electrical conductivity (Wang & Sastry, 1997). Thus heating causes more mobile moisture, increasing ionic mobility, which in turn increases the electrical conductivity. In the case of mushroom, increasing the blanching time from 5 to 6 minutes increased the electrical conductivity, however, on further increasing the blanching time to 7 minutes, electrical conductivity decreased. Notably, mushrooms are known to shrink and lose porosity during blanching, which might explain these results. There was no significant increase in the conductivity of chicken (Figure 3.6). It was observed that chicken typically shrinks and becomes less permeable after blanching as opposed to most vegetable tissue which turns soft. While the ionic content is increased in chicken after blanching, the overall ionic mobility may be reduced due to low permeability, and hence only small increases in the electrical conductivity could be observed. Optimum blanching times (Table 3.5) for conductivity enhancements were determined and the corresponding conductivity plots are as shown in Figure 3.8. We note that differences in particle type include variations not only in size and shape, but also tissue diffusivity differences.
From a comparison of the heating curves of different components of the product with and without blanched solids (Figures 3.9 and 3.10) it may be observed that more uniform heating of the product may be achieved by the pretreatment of solid components. Although the heating of blanched solids is not completely uniform, it represents an improvement over the untreated solids formulation. It is likely that the relatively short blanching times do not allow full equilibration between blanching sauce and solids; indeed salt concentration gradients likely persist in some samples. Heating rates would reflect nonuniformities within individual samples. It is possible to further improve the above blanching protocols by allowing more equilibration time post-blanching. Such a scenario would likely occur in a realistic process setting, where product must be mixed and precooked prior to sterilization. Another approach would be to increase diffusion via Moderate Electric Fields (MEF), high pressure (HP), Pulsed Electric Field (PEF) or vacuum infusion. These are subjects for separate study.

Even though the electrical conductivity of chicken was lower than that of other components, it can be observed that chicken heats faster than some of the other solid components under static ohmic heating. Our results are in agreement with the observations made by Sastry and Palaniappan (1992) for ohmic heating of particulate foods under static conditions. Particles and liquid in the mixture heat at rates depending on relative conductivities of the phases and the volume fractions of the respective phases. Chicken chowmein contains more than 60% solids. Under high-concentration conditions, particles may heat faster than fluid. In the present instance chicken comprises 28% of the total product mass, and may well have sufficient volume fraction to heat significantly. The relatively low heating rates of celery and mushroom may be due in part to
incomplete equilibration during blanching, and in part to the relatively low volume fraction of these solids.

Sensory evaluation results (n = 8) are shown in Table 3.6. The results suggest that samples approached high quality (nearly 7) in all measures, indicating that the blanch procedure does result in a quality product. It was observed that there was no significant difference in the properties of the three samples, and it was therefore decided to use the original formulation for all further studies.

3.5 Conclusions

In multicomponent particulate-liquid food systems like chicken chowmein the sauce is more conductive compared to the solid components. Electrical conductivity of solids can be increased (except chicken) to the level of the sauce by blanching them in highly conductive sauce for different lengths of time. Following pretreatment, it may be possible to uniformly heat the entire product during ohmic heating. Sensory results suggest that such pretreatment does not compromise product quality. The protocols developed in this work will be useful for preparation of other multicomponent products (e.g. particulate-laden soups, or stews) for ohmic heating sterilization.
3.6 Nomenclature

A  cross sectional area of the sample (m$^2$)

I  current flowing through the sample (A)

L  length of the sample (m)

V  voltage across the sample (V)

$\sigma$  electrical conductivity (S/m)

3.7 References


Figure 3.1 - Schematic diagram of the experimental setup; ten ohmic heating cells with relay circuit
Figure 3.2 - Flowchart for pretreatment and subsequent preparation of Chicken Chowmein product.
Figure 3.3 - Electrical conductivity variation with temperature of bean sprouts blanched for different times.
Figure 3.4 - Electrical conductivity variation with temperature of celery blanched for different times.
Figure 3.5 - Electrical conductivity variation with temperature of water chestnut blanched for different times.
Figure 3.6 - Electrical conductivity variation with temperature of chicken blanched for different times.
Figure 3.7 - Electrical conductivity variation with temperature of mushroom blanched for different times.
**Figure 3.8** - Electrical conductivity variation with temperature of blanched solid components, shown together.
Figure 3.9 - Heating rates of different solid components of chicken chowmein with untreated solids.
Figure 3.10 - Heating rates of different solid components of chicken chowmein with blanched solids.
### 3.9 Tables

<table>
<thead>
<tr>
<th>Ingredient</th>
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<tr>
<td>Chicken</td>
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<tr>
<td>Celery</td>
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</tr>
<tr>
<td>Bean sprouts</td>
<td>7.00</td>
</tr>
<tr>
<td>Mushrooms</td>
<td>6.00</td>
</tr>
<tr>
<td>Water chestnuts</td>
<td>6.00</td>
</tr>
<tr>
<td>Chowmein sauce</td>
<td>38.87</td>
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**Table 3.1** - Chicken chowmein product formulation.

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<td>Food starch</td>
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<tr>
<td>Soy sauce</td>
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</tr>
<tr>
<td>Salt</td>
<td>1.29</td>
</tr>
<tr>
<td>Onions, dehydrated</td>
<td>1.29</td>
</tr>
<tr>
<td>Sugar</td>
<td>1.13</td>
</tr>
<tr>
<td>White Pepper</td>
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**Table 3.2** - Formulation of chowmein sauce.
### Table 3.3 - Blanching sauce formulation

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<tr>
<td>Salt</td>
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</tr>
<tr>
<td>Sugar</td>
<td>6.78</td>
</tr>
<tr>
<td>White Pepper</td>
<td>1.08</td>
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### Table 3.4 - Composition of the chowmein sauce.

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</tr>
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<tr>
<td>Water</td>
<td>69.97</td>
</tr>
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<td>Chicken fat</td>
<td>6.17</td>
</tr>
<tr>
<td>Food starch</td>
<td>5.90</td>
</tr>
<tr>
<td>Onions, dehydrated</td>
<td>1.29</td>
</tr>
</tbody>
</table>

63
<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bean sprouts</td>
<td>0.17 [10 s]</td>
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<tr>
<td>Water chestnuts</td>
<td>1.5</td>
</tr>
<tr>
<td>Celery</td>
<td>2.0</td>
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<tr>
<td>Mushrooms</td>
<td>6.0</td>
</tr>
<tr>
<td>Chicken</td>
<td>8.0</td>
</tr>
</tbody>
</table>

**Table 3.5 - Blanching times for different ingredients.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std Dev</td>
<td>Mean</td>
</tr>
<tr>
<td>Appearance</td>
<td>6.7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.9</td>
<td>6.6&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Odor</td>
<td>6.9&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.6</td>
<td>7.1&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Flavor</td>
<td>7.0&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.7</td>
<td>6.9&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Texture</td>
<td>7.0&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.6</td>
<td>6.7&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Overall quality</td>
<td>6.8&lt;sup&amp;e&lt;/sup&gt;</td>
<td>0.5</td>
<td>6.9&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

*9-point hedonic scale, with 9 being ‘like extremely’, and 1 being ‘dislike extremely’.

Sample #1- original formulation
Sample #2- fresh onions instead of dehydrated onions
Sample #3- fresh onions instead of dehydrated onions and brown sugar instead of white sugar.
Mean values in the same row with the same letter are not significantly different (p>0.05 for α = 0.05)

**Table 3.6 - Sensory test results** for three formulations of chicken chowmein containing blanched solids.
CHAPTER 4

SALT DIFFUSION INTO VEGETABLE TISSUE AS A PRETREATMENT FOR
OHMIC HEATING

4.1 Abstract

The apparent diffusion coefficient and equilibrium distribution coefficient of sodium chloride in Chinese water chestnut were determined for salt solution concentrations between 5 and 10% and at temperatures in the range 25-80°C. Equilibrium distribution coefficient values were close to 1.0 and did not depend on salt concentration or temperature. The apparent diffusion coefficient of salt in water chestnut is not dependent on the concentration of the salt solution and significantly increased with temperature (P = 0.001) following the Arrhenius equation. Computational fluid dynamic software was used to determine salt concentration and electrical conductivity profile after blanching pretreatment and heating profile of pretreated water chestnut disc under static ohmic heating condition. After blanching, though concentration and electrical conductivity is not uniformly distributed throughout the solid, it was possible to increase the overall electrical conductivity and heat the solid more rapidly during ohmic heating.
4.2 Introduction

Ohmic or electrical resistance heating involves the application of a cyclical potential to a material, resulting in heat generation due to ionic motion. Ohmic heating has potential applications in the food industry for processing of liquid-solid food mixtures, also termed particulate foods (Palaniappan & Sastry, 2002). In an ohmic heating process for particulate foods, the most desirable situation is that in which the electrical conductivities of fluid and solid particles are equal (Wang & Sastry, 1993 a). Palaniappan & Sastry (1991), and Mitchell & de Alwis (1989) measured electrical conductivity of some solid foods. Ruhlman, Jin & Zhang (2001) reported electrical conductivity of some liquid foods at different temperatures. For particulate foods it can be observed that most vegetables and meats have lower electrical conductivities than liquids. It is possible to increase the electrolytic content within foodstuffs, and raise electrical conductivity by salt infusion via soaking or blanching of solids in salt solution. This may be used as a pretreatment for ohmic heating for particulate foods to obtain more uniform heat treatment, if the composition and other properties of the food are not greatly affected (Palaniappan & Sastry, 1991; Wang & Sastry, 1993 a).

Diffusion of salt in solid foods such as pork, beef and fish has been studied by many researchers (Wistreich, Morse & Kenyon, 1960; Wood, 1966; Del Valle & Nickerson, 1967a, b; Dussap & Gros, 1980). Liu (1992) determined the apparent diffusion coefficient of salt in potato tissue in different sodium chloride concentrations (1-5% w/v) and at temperature between 50°C and 120°C. Drusas & Vagenas (1988) studied salt diffusion in green olives at 20°C and 7-16% w/v salt solutions. Wang & Sastry (1993 b) determined salt diffusivity in potato tissue at 25°C and 1-3% w/v salt
solutions. These researchers studied salt diffusion by soaking vegetable pieces in salt solution at different temperatures and determining the salt uptake by the tissues. This method is time consuming, and it is difficult to determine salt concentration in vegetable tissue. Moreover, diffusion studies were generally made in either lower salt concentration solutions or at lower temperatures. A quicker, simpler, yet accurate method is needed.

For this study we have focused on Chinese water chestnut (CWC), an ingredient in the military’s chicken chowmein formulation, which is currently being investigated for processing by ohmic heating. The methodology could, however be used for any vegetable tissue. CWC is the corm of the sedge that grows in damp conditions. The dark-brown corms are peeled before cooking or canning. The bulk of the edible region consists of starch-rich, thin walled storage parenchyma similar in appearance to potato, interspersed with vascular strands. However, in contrast to potato, CWC is notable for its ability to maintain a firm and crunchy texture after considerable heat treatment during canning or cooking (Parker & Waldron, 1995; Mudahar & Jen, 1991; Parker, C. C., Parker, M. L., Smith & Waldron, 2003). CWC is commonly used in oriental foods and is prized for its crispiness.

The objectives of this study were; to develop a simple method to measure salt diffusion into vegetable tissue, and to investigate diffusion of salt into water chestnut tissue under different levels of sodium chloride concentration (5, 7.5 and 10% w/v) and temperature (25 – 80°C). Higher salt concentration and temperature may reduce the pretreatment time necessary for ohmic heat processing. The diffusion data obtained was used further to solve mass transfer problem, using a Computational Fluid Dynamics (CFD) software package, to predict salt concentration profile in water chestnut disc.
Simulation studies were continued to ohmically heat and determine the temperature profile of the blanched water chestnut disc.

4.3 Materials and Methods

4.3.1 Mathematical Model

The sample is assumed to be a slice of fixed thickness separating two compartments of the same volume, one filled with salt solution (donor) and the other with distilled water (receiver) as shown in Fig. 4.1. The solutions in both compartments are well-agitated and hence infinite mass transfer coefficient is assumed at the interfaces. The governing differential equation is Fick’s Second Law:

$$\frac{\partial C_m}{\partial t} = D_s \frac{\partial^2 C_m}{\partial x^2} \quad \text{for } 0 < x < l \text{ and } t > 0 \quad (4.1)$$

The initial condition is:

$$C_m = 0 \quad \text{for } 0 < x < l \text{ and } t = 0 \quad (4.2)$$

The boundary conditions are:

Across the donor-slice interface the concentrations in the two regions are related by partitioning:

$$C_d = K C_m \quad \text{at } x = 0 \quad (4.3)$$

The above expression is strictly valid under equilibrium conditions. In the present system, the salt concentration in the donor compartment is far higher than that in the receiver, and changes very little with time. Thus, it may be assumed for practical purposes, as an equilibrium situation, permitting use of eq. (4.3) as a boundary condition.
At the receiver-slice interface, however, the salt concentration increases throughout the experimental duration, resulting in a nonequilibrium condition. Thus, partitioning boundary conditions are not appropriate. Instead, the concentration in the receiver volume is given by a mass balance on the receiver-slice interface, yielding a closed problem:

\[ V_i \frac{dM_i}{dt} = AD_i \left. \frac{\partial C_m}{\partial x} \right|_{x=l} \]  

(4.4)

This set of governing equations was discretized using the finite difference method. Central difference was used to discretize the diffusion terms and hence a second order spatial accuracy was maintained. Temporal discretization was done using the second order implicit Crank-Nicholson method. The domain was represented by a grid of 41 nodes. Increasing the number of nodes to 81 led to a negligibly small change (0.02% maximum) in the solution suggesting grid independence was achieved. Convergence was achieved at each time step when the relative change in the solution at successive iteration was less than \(10^{-5}\). Finite difference calculations were performed using Matlab (v. 6.5, Natick, MA).

### 4.3.2 Experimental Procedure

Equilibrium distribution coefficient and apparent diffusion coefficient of sodium chloride in water chestnut were determined at four different temperatures (25, 40, 60 and 80 °C), and for three different salt concentrations (5, 7.5 and 10 % w/v).
4.3.2.1 Determination of equilibrium distribution coefficient (K)

Water chestnut slices 5 mm thick and 18 mm in diameter were used. Beakers containing 100 ml of sodium chloride solution were placed in an agitated water bath. The temperature of the water bath was set to a pre-assigned value. A single CWC slice was placed in each beaker. The beakers were sealed with foil to avoid vaporization. At fixed time intervals one beaker was picked at random and removed from the water bath. Sodium chloride concentration of the solution in the beaker was determined by titration using the Mohr method (Skoog & West, 1976; Williams, 1979). Also, a CWC slice was taken out, crushed in distilled water, and sodium chloride concentration determined by titration.

Equilibrium was assumed to be achieved between the sodium chloride content in the CWC slice ($C_{m\infty}$) and salt solution ($C_{d\infty}$) when there was no further change in the concentrations. The equilibrium distribution coefficient could be determined from $K = C_{d\infty}/C_{m\infty}$. Three replicate experiments were conducted for each temperature and concentration combination.

4.3.2.2 Determination of apparent diffusion coefficient ($D_s$)

CWC slices, 0.5 mm thick and 18 mm in diameter were used. A single sample was mounted in the diffusivity cell between two compartments of 1.25 L volume each, separated by a wall; see Fig. 4.2(a). The CWC disc was held by the holder, as shown in Fig. 4.2 (b). Sodium chloride solution and distilled water were preheated to the desired temperature and 0.950 L of each was poured into separate reservoirs in the diffusivity cell. The cell was placed in a water bath set to the desired temperature, and was covered
with foil to prevent evaporation. The temperature of the solutions was controlled within ±2°C of the pre-assigned temperatures. The solutions in both compartments were continuously stirred to ensure mass transfer coefficient at the interfaces were very high. Sodium chloride diffuses through CWC and enters the receiver region. At fixed time intervals, 5 ml solution from the receiver was withdrawn and the salt concentration was determined by titration. As 5 ml solution was withdrawn every time from the receiver compartment, the receiver volume changes during the experiment. The maximum volume change for the length of the experiment was about 4% and was not accounted for. Two replicate experiments were conducted for each temperature and concentration combination.

The apparent diffusion coefficient \(D_s\) was estimated using the least squares method to minimize the difference between the measured and predicted receiver salt concentration:

\[
S = \sum_{i=1}^{N} (C_i - M_i)^2
\]  

(4.5)

4.3.3 Statistical Analysis

Equilibrium distribution coefficient and apparent diffusion coefficient data were subjected to analysis of variance (ANOVA).

4.3.4 Computational Simulation

4.3.4.1 Blanching

Simulation studies were performed for the 3D case. The sample was assumed to be a water chestnut disc of 7.5 x 10^{-3} m in thickness and 1.8 x 10^{-2} m in diameter. The
governing differential equation is Fick’s Second Law, which for a constant diffusion coefficient reduces to:

\[
\frac{\partial C_m}{\partial t} = D_s \left( \frac{\partial^2 C_m}{\partial x^2} + \frac{\partial^2 C_m}{\partial y^2} + \frac{\partial^2 C_m}{\partial z^2} \right)
\]

(4.6)

The temperature distribution in a solid particle is governed by thermal conduction with no internal heat generation and the equation reduces to:

\[
\rho_s C_p \frac{\partial T_s}{\partial t} = \nabla \cdot (k_s \nabla T_s)
\]

(4.7)

Initial conditions used were; temperature = 298 K, and mass fraction of NaCl = 0.0. Solutions were obtained for two different wall temperature conditions (298 K and 373 K), and both with 0.05 mass fraction of NaCl at the wall (boundary conditions).

4.3.4.2 Blanching followed by ohmic heating

Preliminary simulation studies were performed for the 2D case; the water chestnut disc (0.018m x 0.0075m) placed at the center in the box (0.18m x 0.18m), see Fig. 4.3. Simulations were carried out to determine the salt concentration profile within the water chestnut when blanched in 5% salt solution for 90 s. After the diffusion step, the simulations were continued for static ohmic heating conditions to determine temperatures in the water chestnut disc and the surrounding salt solution.
**Step I:** Blanching pretreatment - salt diffusion in water chestnut

The same simulation procedure was followed as explained in the previous section, with the only difference being that the disc was surrounded by salt solution. Wall boundary conditions were used for the outer walls of the box.

**Step II:** Ohmic heating - heating rates in solid and liquid

Constant voltage (100 Vrms) was applied across the electrodes. Electric field distribution within the ohmic heater was calculated by solving Laplace’s equation;

\[ \nabla.(\sigma \nabla V) = 0 \quad (4.8) \]

with boundary conditions;

\[ V_{|z=0} = V_0, \quad V_{|z=L} = V_L \quad (4.9) \]

Temperature distribution in a heater containing a static medium and a solid particle is governed by thermal conduction with internal heat generation. Thermal balances for the static fluid medium and the solid particle are given by;

\[ \rho_f C_p f \frac{\partial T_f}{\partial t} = \nabla.(k_f \nabla T_f) + \dot{u}_f \quad (4.10) \]

\[ \rho_s C_p s \frac{\partial T_s}{\partial t} = \nabla.(k_s \nabla T_s) + \dot{u}_s \quad (4.11) \]

where the energy generation terms are give as follows;

\[ \dot{u}_f = \sigma_f |\nabla V|^2 \quad (4.12) \]

\[ \dot{u}_s = \sigma_s |\nabla V|^2 \quad (4.13) \]

For salt solution the electrical conductivity is a function of temperature (determined experimentally) and is expressed as;

\[ \sigma_f = \sigma_0 + aT \quad (4.14) \]
Ohmic heating was applied till the center temperature reaches the sterilization temperature which is 140°C. For water chestnut electrical conductivity is a function of temperature. Additionally, the salt concentration is not uniform inside the solid particle and the electrical conductivity will vary with salt concentration. These relationships were determined as follows; electrical conductivity of 5% salt solution was determined using the setup and procedure as described in Chapter 2. Water chestnut discs of 0.018m diameter and 0.0075m thickness were immersed in salt solutions of different concentrations (0, 2.5 and 5%) and allowed to equilibrate at room temperature for 24 hrs. (enough time for salt equilibration). Electrical conductivity of the samples was determined using the setup and procedure described in Chapter 2. Three replicates were conducted for each salt concentration.

For 5% salt solution the electrical conductivity is a linear function of temperature (Fig. 4.4) and is given as;

$$\sigma_j = -31.848 + 0.132(T) \quad (4.15)$$

Electrical conductivity of water chestnut increased with temperature and salt concentration, see Fig. 4.5. The relationship of electrical conductivity with temperature and salt concentration is found to be; \([R^2=0.98]\)

$$\sigma_s = -9.085 + 0.038(T) + 144.586(C) - 3.346\times10^{-5}(T^2) - 1.150\times10^3(C^2) \quad (4.16)$$

The relationship of electrical conductivity with temperature and salt concentration was thereby obtained and used in the simulation studies.

4.3.4.3 Ohmic heating of unblanched solid

Unblanced water chestnut was ohmically heated and the heating rates were compared with that of the blanched water chestnut.
Commercial software FLUENT® 6.1 along with meshing software, GAMBIT® 2.0 (Fluent Inc., NH, USA) was used to obtain numerical solution to equations 4.6, 4.7, 4.10 and 4.11. The criteria for convergence used in the CFD simulation were $10^{-8}$ for species concentration and $10^{-7}$ for energy. The Laplace equation was solved by using the user-defined scalar (UDS) option. The heat source terms for solid and liquid due to the resistive heating was introduced by adding a numerical code by using the user-defined function capability of FLUENT.

4.4 Results and Discussion

4.4.1 Equilibrium diffusion coefficient

An example plot of changes in the salt concentration with time in the solution ($C_d$) and CWC ($C_m$), for the determination of equilibrium distribution coefficient ($K$), is shown in Fig. 4.6. Salt concentration in the solution remained essentially constant, while, salt concentration in the CWC increased with time until reaching equilibrium. Table 4.1 gives average values of the equilibrium distribution coefficient ($K$) based on the 3 replicates. The range of values was between 1.04 and 1.09, and did not change significantly with salt concentration of the solution ($p = 0.985$) or temperature ($p = 0.493$). Wang & Sastry (1993 a) reported $K$ values of salt in potato at 25°C and different salt concentrations (1 to 3% w/v). In contrast to these CWC results, they found that $K$ decreased from 2.43 for 1% salt solution to 1.36 for 3% salt solution concentration.
4.4.2 Apparent diffusion coefficient ($D_s$)

Diffusion experimental data are shown in Fig. 4.7a, b, c and d. At all temperature settings, as the salt concentrations in the donor compartment increased the amount of sodium chloride that diffused into the receiver compartment increased. An example plot of the diffusion experimental data and fitted curves by using eq. 4.1 for two cases (5%, 25°C and 10%, 80°C), is shown in Fig. 4.8. Fig. 4.9 compares the predicted salt concentration $[M_f]$ for the final $D_s$ values, and the experimentally determined salt concentrations $[C_i]$. The satisfactory fit of the predicted salt concentrations to the experimental values suggests that Fick’s law can be used to describe the diffusion process of salt in CWC tissue. Some deviation was observed at higher concentrations (long times). This may be due to the textural changes when CWC is exposed to higher temperatures for longer times. The calculated apparent diffusion coefficient ($D_s$) values are summarized in Table 4.1. Concentration and temperature dependence of the apparent diffusion coefficient of salt in CWC is shown in Fig. 4.10. At the same temperature, the apparent diffusion coefficient does not vary significantly with concentration ($p = 0.937$). A significant increase ($p = 0.001$) in the apparent diffusion coefficient was observed with a rise in temperature from 25°C to 80°C.

The change in diffusion coefficient of salt in CWC with temperature can be described by the Arrhenius equation:

$$D_s = D_0 \exp \left( -\frac{E}{RT} \right) \quad (4.17)$$

The Arrhenius plots are shown in Fig. 4.11, with the estimated constants summarized in Table 4.2. The average activation energy was 12.7 kJ mol$^{-1}$, and did not change significantly with changes in salt solution concentration. High values of the coefficient
of determination, $R^2 (>0.99)$ were obtained for all cases over the temperature range 40 to 80°C. When diffusivities at 25°C are included, the fit to the Arrhenius plot is only slightly weakened ($R^2 = 0.97$).

To our knowledge, there are no literature data on diffusion coefficients of salt in CWC. It may be instructive to compare our values ($7.5–18.5 \times 10^{-10} \text{ m}^2 \text{s}^{-1}$) against literature values for some other materials. The average value of apparent diffusion coefficient of sodium chloride in potato at 25°C was $4.2 \times 10^{-10} \text{ m}^2 \text{s}^{-1}$ (Wang & Sastry, 1993a). Liu (1992) measured apparent diffusion coefficient of sodium chloride in potato at temperatures in the range 50 to 120°C and under 1 to 5% w/v salt concentrations. Values were in the range of $2.51-41.8 \times 10^{-10} \text{ m}^2 \text{s}^{-1}$. It was observed that the apparent diffusion coefficient of salt in potato was temperature dependent and followed the Arrhenius equation, with activation energies 20 to 24 kJ mol$^{-1}$ that decreased with increasing concentration. Coefficients of determination ($R^2$) larger than 0.98 were observed for all the cases over the temperature range 70 to 120°C. When the diffusivities at 50°C and 60°C in 3% salt solution were included, the Arrhenius plot fit was poorer ($R^2 = 0.81$). Liu (1992) observed that over the temperature range 50 to 70°C, dramatic changes take place in the potato because of denaturation of the cell membrane and gelatinization of the starch granules, with the resultant destruction of the cell walls. Such changes in potato above 70°C are completed within a very short period. Comparing our diffusion results for CWC with that for potato reported by Liu (1992), suggests that there may be some textural changes in CWC at higher temperature, but the change is not as prominent as observed for potato. Also, unlike potato which tends to soften upon cooking, CWC retains crunchiness which is consistent with small changes in diffusion

4.4.3 Simulation

The parameters and properties used for simulation are listed in Table 4.3. Apparent diffusion coefficient was found to be a function of temperature and the equation is as shown in Table 4.3, where temperature is in degree Kelvin. Protein, carbohydrate, fat, ash and moisture content in water chestnut were obtained from USDA Handbook (USDA, 2005, online) and are listed in Table 4.4. Specific heat was calculated using the equation given by Singh and Heldman (1984);

\[ C_p = 1.424m_c + 1.549m_p + 1.675m_f + 0.837m_a + 4.187m_m \]  \hspace{1cm} (4.18)

4.4.3.1 Blanching

Initially temperature of the disc was 298 K and the diffusion constant is small. When disc is exposed to 373 K wall temperature, with time, temperature of the disc increases (Figure 4.12), and \( D_s \) value increases with temperature. After 90 s, temperature within the disc is almost uniform at 373 K (Figure 4.13). Concentration profile in water chestnut disc after 90 s is as shown in Figure 4.14. It can be observed that after 90 s, which is the blanching time for water chestnut (Chapter 3), salt has diffused only to certain depth in the disc and concentration in the interior is essentially zero. If allowed to equilibrate, it was found that, at 373 K wall temperature, the equilibration time is 5400 s (90min). The equilibration time is 15600 s (260min) for 298 K wall temperature condition.
4.4.3.2 Ohmic heating

Fig. 4.15, shows the salt concentration profile inside the chestnut disc after 90 s blanching in 5% salt solution. Salt concentration was maximum at the surface and was essentially zero in the interior. Temperature was approximately 373K inside the disc (Fig. 4.16). Before the actual ohmic heating step the entire system was cooled so that the temperature throughout the fluid and solid was 338K (temperature at which the preheated product will enter the ohmic heater). Electrical conductivity of the chestnut decreases from the surface to the interior and its profile is shown in Fig. 4.17. A constant voltage of 100 Vrms was applied across the electrodes and the contours of temperature in and around the chestnut disc is shown in Fig. 4.18. Temperature at the interior of the solid disc reached sterilization temperature (140°C) within 100 s of ohmic heating. Contours of temperature in and around the ohmically heated unblanched chestnut disc are shown in Fig. 4.19. These temperatures at the center were 12°C lower than the corresponding temperature within an unblanched disc. This shows the efficacy of a blanching pretreatment in improving the ohmic process, even if salt equilibration is incomplete.

4.5 Conclusions

Fick’s law of diffusion can be used to describe sodium chloride diffusion in CWC. Equilibrium distribution coefficient values were close to 1.0 and did not change significantly with salt concentration or temperature of the solution. The apparent diffusion coefficient of sodium chloride in CWC was found to be $7.5 \times 10^{-10}$ m$^2$s$^{-1}$. The apparent diffusion coefficient of salt in CWC changed significantly with temperature and can be adequately described by the Arrhenius equation. Although simulation studies
show that under blanching conditions, after 90 s, salt diffused only to a small depth, simulation of ohmic heating reveal that blanched solids heat considerably faster than unblanched solids. Thus, even an incompletely equilibrated blanch pretreatment is beneficial.

4.6 Nomenclature

\( A \) sample surface area (m\(^2\))

\( C \) salt mass fraction

\( C_d \) salt concentration in the donor compartment (moles m\(^{-3}\))

\( C_{d,\infty} \) salt concentration in the donor solution at equilibrium (moles m\(^{-3}\))

\( C_m \) salt concentration in the sample (moles m\(^{-3}\))

\( C_{m,\infty} \) salt concentration in the sample at equilibrium (moles m\(^{-3}\))

\( C_i \) experimental salt concentration in the receiver at fixed time interval (moles L\(^{-1}\))

\( C_p \) specific heat (kJ/kg K)

\( D_0 \) reference temperature diffusion coefficient constant (m\(^2\) s\(^{-1}\))

\( D_s \) apparent diffusion coefficient (m\(^2\) s\(^{-1}\))

\( E \) activation energy (J mol\(^{-1}\))

\( k \) thermal conductivity (W/mK)

\( K \) equilibrium distribution coefficient

\( l \) thickness of the sample (m)

\( M_i \) predicted salt concentration in the receiver at fixed time interval (moles L\(^{-1}\))

\( m \) mass fraction

\( N \) number of experimental measurements
\( R \)  Universal gas constant (J mol\(^{-1}\) K\(^{-1}\))

\( S \)  sum of squared differences between measured and predicted values

\( t \)  time (s)

\( T \)  absolute temperature (K)

\( u \)  specific internal energy generation rate (W/m\(^3\))

\( V \)  voltage (V)

\( V_d \)  volume of solution in donor compartment (L)

\( V_r \)  volume of solution in receiver compartment (L)

\( x \)  distance from the donor-sample interface (m)

\( \rho \)  density (kg/m\(^3\))

\( \sigma \)  electrical conductivity (S/m)

Superscripts/subscripts

\( f \)  fluid phase

\( s \)  solid phase
4.7 References


4.8 Figures

Figure 4.1 - Schematic diagram of the diffusion model
Figure 4.2 - (a) diffusivity cell, and (b) sample holder details
**Figure 4.3** – Schematic diagram of chestnut disc in box used for simulation studies.
Figure 4.4 – Electrical conductivity variation with temperature of 5% salt solution.
Figure 4.5 – Electrical conductivity variation with temperature, of water chestnut with 0.015, 2.5 and 5% salt mass fraction.
Figure 4.6 - Salt concentration change in the solution ($C_d$) and CWC ($C_m$) for determination of $K$ (3 replicates at 5% salt concentration and 25°C).
Figure 4.7 - Change in salt concentration in the receiver with time for three salt solutions at (a) 25°C; (b) 40°C; (c) 60°C and (d) 80°C.
Figure 4.8 - Change in salt concentration in the receiver with time; (♦) 5% and 25°C, (▲) 10% and 80°C, and (→→) theoretical lines.
**Figure 4.9** - Comparison of the predicted salt concentration \([M_i]\) for final \(D_s\) values and the salt concentration determined experimentally \([C_i]\).
Figure 4.10 - Concentration and temperature dependence of the apparent diffusion coefficient ($D_s$) of salt in CWC.
Figure 4.11 - Arrhenius plots for apparent diffusion coefficient ($D_s$) where $T$ is the absolute temperature
Figure 4.12 - Contours of temperature for the water chestnut disc after 10 s of blanching, shown in the y-z plane.
**Figure 4.13** - Contours of temperature for the water chestnut disc after 90 s of blanching, shown in the y-z plane.
Figure 4.14 - Contours of salt concentration for the water chestnut disc after 90 s of blanching, shown in the y-z plane.
Figure 4.15 – Contour of salt concentration in water chestnut disc after blanching pretreatment of 90 s.
Figure 4.16 – Contour of temperature within and around the water chestnut disc after the blanching pretreatment of 90 s.
Figure 4.17 – Contour of electrical conductivity inside the chestnut disc.
**Figure 4.18** – Contour of temperature within and around the blanched water chestnut disc after 100 s of ohmic heating.
Figure 4.19 – Contour of temperature within and around the unblanched water chestnut disc after 100 s of ohmic heating.
### Table 4.1 - Equilibrium distribution coefficient ($K$) and diffusion coefficients ($D_s$) of sodium chloride in CWC tissue at four temperatures and three concentrations of salt

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>Salt conc. (wt/v %)</th>
<th>$K$</th>
<th>$D_s$ ($10^{-10}$ m$^2$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>5</td>
<td>1.09</td>
<td>7.5</td>
</tr>
<tr>
<td>25</td>
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<td>80</td>
<td>7.5</td>
<td>1.07</td>
<td>17.5</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>1.08</td>
<td>18.5</td>
</tr>
</tbody>
</table>

### Table 4.2 - Activation energy ($E$) and reference temperature constant ($D_0$) for diffusion of sodium chloride in CWC

<table>
<thead>
<tr>
<th>Salt conc. (w/v %)</th>
<th>$E$ (kJ mol$^{-1}$)</th>
<th>$D_0$ ($10^{-6}$ m$^2$s$^{-1}$)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>12.7</td>
<td>1.37</td>
<td>0.989</td>
</tr>
<tr>
<td>7.5</td>
<td>12.4</td>
<td>1.29</td>
<td>0.981</td>
</tr>
<tr>
<td>10</td>
<td>13.0</td>
<td>1.63</td>
<td>0.971</td>
</tr>
<tr>
<td>Overall</td>
<td>12.7</td>
<td>1.43</td>
<td>0.924</td>
</tr>
</tbody>
</table>

**4.9 Tables**
Density of water chestnut (kg/m$^3$) 995
Thermal conductivity of water chestnut (W/mK) 0.485
Specific heat of water chestnut (kJ/kgK) 3478
Diffusivity (m$^2$/s) $2 \times 10^{-11}(T) - 4 \times 10^{-9}$
Mass fraction of NaCl at the wall 0.05
Initial mass fraction of NaCl 0
Initial Temperature (K) 298

Table 4.3 - Values of parameters used for simulation

<table>
<thead>
<tr>
<th>Percent weight</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>74.28</td>
</tr>
<tr>
<td>Proteins</td>
<td>1.41</td>
</tr>
<tr>
<td>Carbohydrates</td>
<td>24.21</td>
</tr>
<tr>
<td>Fats</td>
<td>0.10</td>
</tr>
<tr>
<td>Ash</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 4.4 - Composition data for water chestnut (raw) (USDA Handbook, 2005)
5.1 Abstract

The Residence Time Distribution (RTD) of a model particulate-fluid mixture (potato in starch solution) in the ohmic heater in a continuous sterilization process was measured using a Radio Frequency Identification (RFID) methodology. The effect of solid concentration and the rotational speed of the agitators on the RTD were studied. The velocity of the fastest particle was 1.62 times the mean product velocity. In general, particle velocity was found to be greater than the product bulk average velocity. Mean particle residence time increased with increase in the rotational speed of the agitators ($p < 0.05$) and no particular trend was observed between the mean particle residence time and the solid concentration. The distribution curves $E(\theta)$ were skewed to the right suggesting slow moving zones in the system.
5.2 Introduction

In continuous sterilization processes critical parameters include the temperature of the coldest spot in the food and the shortest particle residence time in heating and holding sections. Measurement of residence time distribution (RTD) is needed for determination of the fastest-moving particle, to be used for designing and biologically validating processes. Residence times of the average and slowest food elements helps in evaluating quality degradation.

The critical safety consideration is that of the fastest-moving particle: the RTD experiment must be able to demonstrate with a high degree of confidence (95 %) that the fastest (99th percentile) particle has indeed been sampled and therefore the sample size becomes critical. DiGeronimo et al. (1997) stated that a distribution-free method was the most appropriate method to determine reliably the characteristic fastest particle of the system. Palaniappan & Sizer (1997) determined with 95% confidence that the fastest 99th percentile particle was sampled, a population size of 299 particles is necessary.

Most studies on RTD have focused on visualization or detecting flow of particles either within or at the inlet and outlet of process equipment. Alhamdan & Sastry (1997), Salengke & Sastry (1995), Salengke & Sastry (1996), Dutta & Sastry (1990a,b), McCoy et al. (1987), and Sancho & Rao (1991) studied RTD of food particles in holding tube. A number of published studies have addressed residence times in swept surface heat exchanges (SSHE) (Alhamdan & Sastry, 1998; Lee & Singh, 1991; Chandarana & Unverferth, 1996).

Only a few experiments have been performed on RTD in ohmic heating systems. RTD of particulates in ohmic system was investigated by Kim et al. (1996) both visually

Three categories of variables which can affect RTD of particles in particulate system are identifiable, those associated with the physical system, particles, and the carrier fluid. System variables include dimensions, orientation, rotational speed of agitators and product flow rate; particle variables include concentration, size, shape, type and density; and the principal fluid variable involves rheological properties. System variables like dimensions and orientation of heaters are generally fixed for the ohmic heating facility. There is a need to study, in detail, the effect of other variables.

Several techniques have been developed for investigating the RTD of solid-liquid flow as reviewed by Ramaswamy et al. (1995) and Sastry & Cornelius (2002). These include visual observation (for example, stop watch, photography, playback videotaping), laser beam detection, radioactive tracers, magnetic response, and photo sensors methodology. Most methods work at low temperatures although recent investigations have been performed at high temperatures. Generally, the majority of published results were for a low proportion of solids with respect to liquid. A popular technique with the industry is the use of magnetic methods which involve introduction of tagged particles containing small magnets (Segner et al., 1989; Chandarana & Unverferth, 1996). The passage of these tagged particles is detected by a voltage generated within coils at
selected locations of the process equipment. Hall effect sensors also operate on a similar principle of electromagnetic induction (Tucker & Withers, 1994). Magnetic resonance techniques have also been used for flow visualization in food systems (Manavel et al., 1993). Optical methods like particle tracking velocimetry (Zitoun et al., 2001) and other visualization techniques have also been used. Researchers have also examined history methods, such as chemical markers and thermal memory cells, which involve determining the effect of a process on a chemical reaction or diffusion process and back calculating processing parameters (Kim & Taub, 1993; Swartzel et al., 1991). Other methods for measuring RTD are ultrasound methods, which involve detecting RTD by Doppler scattering of ultrasound waves by the moving particles, and salt tracer methods, where the RTD is measured by electrical conductivity measurements (Ramaswamy et al., 1995).

In industry, magnetic particle methods have achieved greater acceptance than the other methods because of their simplicity, versatility, relative ease of implementation and low cost. However, their principal limitation is the inability to distinguish between multiple particles passing through the detector at the same time. This necessitates that operator wait for each magnetic tracer to enter and exit the system before introduction of the next tracer (Sastry & Cornelius, 2002).

Radio Frequency Identification (RFID) technology contains tags, each with a unique serial number or an Electronic Product Code (EPC), which can be read by the reader (Bhuptani & Moradpour, 2005; Heinrich, 2005; and Paret, 2005). Since each tag has a unique code, multiple particles with embedded RFID tags can be introduced in the food processing system at the same time for RTD measurement. One reader can be
placed at the inlet and another at the outlet of the system across which the RTD is to be measured. When the particle containing the RFID tag passes through the reader, the EPC code is transmitted to the reader, and the time of transmission is recorded. The difference between the time recorded at the inlet and the outlet reader provides residence time for that particle. RFID technique, where in it is possible to track multiple particles, could be used to measure RTD of particles in the ohmic heater in a continuous sterilization process. Grabowski et al. (1993) patented similar approach for measuring RTD. The limitation of their studies was that the transponders they used were of the order of 0.0254 m long and 0.00356 m diameter making them longer than the normally desirable processed food particles. Today the availability of small and lighter transponders, make RFID technique attractive for measuring RTD of food particles. Tulsiyan et al. (2007) used RFID methodology to determine RTD of chicken particles in ohmic heating system. The use of RFID tracers obviated the waiting time that was needed for a magnetic tracer to exit the system before the next magnetic tracer can be introduced.

The objective of this study was to study the effect of concentration of solids (30, 40, 50, 60, 70, and 80 % v/v) and rotational speed of the agitators (55, 40, and 25 rpm) on the RTD of particles in a solid-liquid food mixture (potato in starch solution) in a pilot-scale ohmic heater.
5.3 Materials and methods

5.3.1 Product

The product chosen for this study was potato solids in starch solution. Diced frozen potatoes (5/8 inch) were procured from E.W. Carlberg Co. (Kansas City). The carrier fluid was a starch solution with 6 %w/w starch (PURITY CLOUD®, National Starch, Bridgewater, NJ) and 0.45 %w/w NaCl salt (Cargill, Minneapolis, MN). Frozen potatoes were blanched for 30 s in 3 %w/w NaCl salt solution at about 98°C, to raise the temperature and to increase the electrical conductivity and match it to the carrier fluid. The formulation was finalized based on preliminary experimental results, to obtain a viscous carrier fluid and closely match the conductivities of solid and fluid phases.

5.3.2 Analog particles

Potato/alginate analog particles carrying RFID tags were used as tracers for the RTD studies. The potato/alginate cubes were prepared by adaptation of the formula used by Brown et al. (1984). Canned sliced potatoes (The Kroger Co., Cincinnati, OH) were drained and mashed in a blender and mixed to obtain potato/alginate blend. The finished potato/alginate blend was shaped into a 5/8” slab. RFID tags were inserted into the slab at equal distances (5/8”) and the slab was immersed in a 2 % calcium chloride solution overnight at 4°C to harden. After hardening, the slab was then cut into 5/8” cubes (such that each RFID tag was at the center of the cube). The analog particles thus obtained were stored in calcium chloride solution at refrigerated temperature until use. A colored food-dye (The Kroger Co., Cincinnati, OH) was added to the mixture to help identify the tracers for recovery of the RFID tags after the experiment.
Electrical conductivity of the particles so obtained was found to be significantly higher than the blanched potato particles and the gelatinized starch solution. In order to adjust the conductivity, while still maintaining the density and rigidity of the particles, different formulations were prepared containing vegetable oil, polystyrene beads (125 – 212 μm) or sand (15 – 150 μm), in different proportions. The formulation was finalized based on these preliminary experiments to obtain analog particles of the same density and electrical conductivity as the blanched potato solids and the carrier fluid. The formulation is shown in Table 5.1.

Density was determined by weight/volume method and the density of potato/alginate particles was within 2.7% of the blanched potato solids. An electrical conductivity comparison of the starch solution, blanched potatoes, and potato/alginate analog particles is shown in Figure 5.1. Electrical conductivity of 10 samples each was determined using the experimental setup and procedures explained in Chapter 2. Statistical analysis showed that there was no significant difference in the electrical conductivities of the three components (p > 0.05).

5.3.3 Ohmic heating pilot plant facility

Experiments were performed on a 54 kW industrial ohmic heating pilot plant with small modifications to the system to accommodate the RFID readers. The installation consisted of two mixing tanks, a magnetic flow meter (Rosemount Inc, Chanhassen, MN, USA), heating column, swept surface heat exchanger (SSHE) (Waukesha Cherry-Burrell, Delavan, WI, USA), holding tube, and aseptic catch tank (see Figure 5.2). The heating column consisted of three ohmic heaters with each heating section housed between a pair of electrodes.
5.3.4 Radio Frequency Identification (RFID)

Cylindrical shaped RFID tags (GLT12x2RO, Intersoft Corp, Tullahoma, TN, USA), measuring 0.012m in length and 0.002m in diameter, and weighing 0.0001 kg were used. The tags operated at 125 kHz frequency which is considered least susceptible to metal and liquid interference. The RFID reader consisted of a reader module (TRRO1OEM, Intersoft Corp, Tullahoma, TN, USA) and a circular antenna (Intersoft Corp, Tullahoma, TN, USA) connected to the module board.

In the pilot plant facility, the metal tubes present at the inlet and outlet of the ohmic heating column were replaced by glass tubes. This is necessary to minimize the attenuation that radio frequency suffers near metal. One antenna was placed at the inlet of the heater and a second antenna at the outlet (Fig. 5.2). A RFID reader was connected to each antenna. Both readers were connected to a computer for data acquisition. The software used for data acquisition was a modified version of the software provided by the RFID vendor (tstdemo2.exe, Intersoft Corp, Tullahoma, TN, USA) which would record the EPC serial code of the tags and the time the code is read.

5.3.5 Experimental method

All the variables and parameters of this study are listed in Table 5.2. In a separate set of preliminary experiments the bulk conductivity of the product (with different solid concentrations) was determined using a bench scale 2 inch static ohmic heater (the setup described in Chapter 3). Electrical conductivity of different concentrations of sodium sulfate solution in water (sterilizing fluid) was also determined. Different sodium sulfate solution concentrations that match the electrical conductivity of the different products are listed in Table 5.3.
Sodium sulfate solution of the required concentration was prepared in a mixing
tank, pumped through the system and ohmically heated. System conditions, such as flow
rate (1.9 gal/min), inlet temperature to the heaters (55°C), outlet temperature from the
heaters (130°C) and outlet temperature from heat exchangers (approximately 30°C) were
set using this salt solution.

Starch solution was first cooked and gelatinized at about 70°C in a separate
mixing tank. Frozen potatoes were blanched separately for 30 s in 3 % w/w salt solution at
boiling temperature. Blanched potatoes along with potato/alginate analog particles were
then added to the gelatinized starch solution and mixed in the mixing tank. Although data
were only needed for 299 intact particles, 600-650 tracers were added in the mixing tank
and mixed thoroughly with the product. The extra tracers were added to provide a margin
of safety, since not all particles that remained fully intact would be read by the readers at
both the inlet and the outlet of the ohmic heaters. Once the product temperature was 55°C
(similar to the inlet condition of sodium sulfate solution) product was pumped through
the system. Generally, a half hour of mixing was allowed between mixing the solids in
cooked starch solution and pumping the product. This time was considered enough to mix
the product properly. The product, along with the tracers, was heated to aseptic
processing temperature (130°C) in the ohmic heaters, held in the holding tube, cooled in
the SSHE and water cooled tube heat exchangers, and finally collected in the aseptic
tank.

When the RFID tag-containing tracers passed through the reader antenna, the
reader powered the tags which then transmitted their EPC serial code to the reader, which
was recorded by the data acquisition system. The time at which the EPC was transmitted
was also recorded. The difference between the time recorded at the inlet and the outlet reader for a tracer gave the residence time for that tracer particle. Data was collected for minimum 299 intact particles, under each experimental condition.

The product flow rate was fixed through the experiments at 1.2 m$^3$/s (1.9 gal/min). Knowing the volume between the two readers the mean product residence time was calculated to be 94 s. Once the entire product was pumped through the heaters, the line was switched back to sodium sulfate solution and heating was stopped. Product was collected in the aseptic tank from which the particles containing RFID tags were retrieved. The experiment was repeated for different solid concentrations and rotational speed settings.

5.4 Results

Three levels of rotation speed of agitators on ohmic heaters (55, 40, and 25 rpm) and six levels of solid concentrations (30, 40, 50, 60, 70 and 80 % v/v) were studied for their effect on the RTD of particles in ohmic heaters. After the experiments were completed for solid concentrations up to 60% solid concentration it was observed that solid concentration did not affect RTD significantly (which will be discussed shortly). Hence, 70 and 80 % v/v solid concentration studies were performed only at one rotational speed of the agitators (40 rpm). With 80 % solids the resulting product was very thick and viscous. It was difficult to pump this product while maintaining the flow rate, final processing temperature, and the pressure in the system constant. The run was aborted and residence time data could not be collected.
Tables 5.4, through 5.9 summarize the effect of the variables studied, on the minimum particle residence time, minimum normalized particle residence time (MNNPRT), mean particle residence time (MPRT), mean normalized particle residence time (MNPRT), maximum particle residence time (MXPRT) and maximum normalized particle residence time (MXNPRT) respectively. The normalized times were calculated by dividing the particle residence times with the mean product residence time (94 s).

The fastest particle residence time was 58 s, or the velocity of the fastest particle was 1.62 times the mean product velocity. The fastest particle was therefore substantially below the limit of laminar flow of Newtonian fluids in cylindrical tube, where the maximum velocity in the center of the tube can reach twice the mean velocity. In most of the cases the mean normalized particle residence time (MNPRT) (see Table 5.7) was less than the mean product residence time, which implies that average particle velocities are faster than the bulk product velocity. In all runs, the MXPRT was found to be 188 s or the MXNPRT was 2.00. This implies that the slowest moving particle is twice as slow as the bulk product.

Mean particle residence time (MPRT) increased with increase in the rotational speed of the agitators (p < 0.05), see Table 5.6. Also, the statistical analysis shows that MPRT are affected significantly by the solid concentration (p < 0.05), however, no particular trend was observed between the mean residence time and the solid concentration.

The density function $E(\theta)$, for the normalized residence time are plotted for all cases and shown in Figure 5.3 through 5.15. These plots illustrate the spread of the residence time distributions from the mean and also help to examine its departure from
the ideal plug flow behavior. It can be observed that in all the cases the $E(\theta)$ curves are skewed to the right and, in general, at higher solid concentrations the distribution becomes narrower. Tusiyan et al. (2007) observed similar tailing effects when they measured the RTD of chicken particles in chicken chowmein in the same ohmic heating system. In their studies the MXNPRT was 1.48, and they reasoned that it might be due to the flow variation that was observed. Similar observations were made by Alhamdan & Sastry (1998) and Lee & Singh (1991) when they studied RTD of solids in swept surface heat exchanger (SSHE). The tailing effect is due to the lag of some particles related to the bulk product which might suggest the presence of some slow moving zones in the ohmic heating system.

The effect of other variables like different types and shapes of particles, and different viscosity of the carrier fluid on the RTD inside the ohmic heaters needs to be investigated. Although we kept the starch concentration and hence initial viscosity of the carrier fluid constant, it should be observed that starch from the blanched potatoes leach out, especially when we mix the product for about half an hour before pumping. This changes the viscosity of the product significantly, especially at higher solid concentrations. To investigate the influence of the solid concentration alone on the RTD, food solids that would not alter the viscosity of the carrier fluid could be used, although it might compromise the ‘real world’ character of experiments.
5.5 Conclusions

Mean particle residence time increased with the rotational speed of the agitators \((p < 0.05)\) and no particular trend was observed between the mean residence time and the solid concentration. The velocity of the fastest particle was 1.62 times the mean product velocity while the product mean velocity was 2.00 times the slowest particle velocity. These values are important for food safety and quality design considerations.

5.6 References


heating. *Journal of Food Science: Food Engineering and Physical Properties* 65 (7), 1180-1186


Figure 5.1- Electrical conductivity comparison of blanched potato particles, starch solution and potato/alginate analog particles (error bars – 1 std. dev.)
Figure 5.2- Diagram of the 54 kW ohmic heating pilot plant facility and position of RFID readers
Figure 5.3 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 30% and 25 rpm.
Figure 5.4 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 30% and 40 rpm
Figure 5.5 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 30% and 55 rpm
Figure 5.6 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 40% and 25 rpm
Figure 5.7 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 40% and 40 rpm
Figure 5.8 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 40% and 55 rpm
Figure 5.9 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 50% and 25 rpm
Figure 5.10 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 50% and 40 rpm
Figure 5.11 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 50% and 50 rpm
Figure 5.12 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 60% and 25 rpm
Figure 5.13 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 60% and 40 rpm
Figure 5.14 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 60% and 55 rpm
Figure 5.15 – Density function $E(\theta)$ of the normalized particle residence time in the ohmic heater; 70% and 40 rpm
5.8 Tables

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Percentage (w/w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canned sliced potato</td>
<td>90.88</td>
</tr>
<tr>
<td>Alginic acid (sodium salt)</td>
<td>3.75</td>
</tr>
<tr>
<td>Sand</td>
<td>5.00</td>
</tr>
<tr>
<td>Calcium sulfate</td>
<td>0.30</td>
</tr>
<tr>
<td>Tri-sodium citrate</td>
<td>0.07</td>
</tr>
</tbody>
</table>

**Table 5.1** – Formulation of the potato analog particles

<table>
<thead>
<tr>
<th>Variables/Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product flow rate</td>
<td>1.2 m$^3$/s (1.9 gal/min)</td>
</tr>
<tr>
<td>Rotational speed of agitators</td>
<td>55, 40, and 25 rpm</td>
</tr>
<tr>
<td>Particle type</td>
<td>Potato</td>
</tr>
<tr>
<td>Particle size</td>
<td>5/8 inch (1.56 cm)</td>
</tr>
<tr>
<td>Particle shape</td>
<td>cube</td>
</tr>
<tr>
<td>Particle density</td>
<td>1130 kg/m$^3$</td>
</tr>
<tr>
<td>Particle concentration</td>
<td>30, 40, 50, 60, 70, and 80 % v/v</td>
</tr>
<tr>
<td>Carrier fluid</td>
<td>6% w/w starch, 0.45% w/w salt</td>
</tr>
<tr>
<td>Final processing temperature</td>
<td>130°C</td>
</tr>
</tbody>
</table>

**Table 5.2** – Specifications of the particles and values of the variables
Table 5.3 – Sodium sulfate solutions having same electrical conductivity as the different products tested.

<table>
<thead>
<tr>
<th>Concentration of solids % v/v</th>
<th>Sodium sulfate concentration % w/w</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.80</td>
</tr>
<tr>
<td>40</td>
<td>0.85</td>
</tr>
<tr>
<td>50</td>
<td>0.90</td>
</tr>
<tr>
<td>60</td>
<td>0.95</td>
</tr>
<tr>
<td>70</td>
<td>1.00</td>
</tr>
<tr>
<td>80</td>
<td>1.05</td>
</tr>
</tbody>
</table>
Table 5.4 - Minimum particle residence time in seconds - the effect of concentration of solids and the rotational speed of the agitators

<table>
<thead>
<tr>
<th>Concentration of solids (% v/v)</th>
<th>Rotational speed of agitators (rpm)</th>
<th>25</th>
<th>40</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>59</td>
<td>64</td>
<td>60</td>
<td></td>
</tr>
<tr>
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<td>58</td>
<td>59</td>
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<td></td>
</tr>
<tr>
<td>50</td>
<td>61</td>
<td>63</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>64</td>
<td>66</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>70</td>
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<td>66</td>
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</tr>
<tr>
<td>80</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5 - Minimum normalized particle residence time (MNNPRT) based on the product mean residence time of 94 s - the effect of concentration of solids and the rotational speed of the agitators

<table>
<thead>
<tr>
<th>Concentration of solids (% v/v)</th>
<th>Rotational speed of agitators (rpm)</th>
<th>25</th>
<th>40</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.628</td>
<td>0.681</td>
<td>0.638</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.617</td>
<td>0.628</td>
<td>0.628</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.649</td>
<td>0.670</td>
<td>0.638</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.681</td>
<td>0.702</td>
<td>0.702</td>
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<tr>
<td>70</td>
<td>-</td>
<td>0.702</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>-</td>
<td>-</td>
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<td></td>
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</tbody>
</table>
Table 5.6 - Mean particle residence time* (MPRT) in seconds - the effect of concentration of solids and the rotational speed of the agitators

<table>
<thead>
<tr>
<th>Concentration of solids (% v/v)</th>
<th>Rotational speed of agitators (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>90.63&lt;sup&gt;a,b,1&lt;/sup&gt;</td>
</tr>
<tr>
<td>40</td>
<td>90.96&lt;sup&gt;a,b,1&lt;/sup&gt;</td>
</tr>
<tr>
<td>50</td>
<td>92.73&lt;sup&gt;a,1&lt;/sup&gt;</td>
</tr>
<tr>
<td>60</td>
<td>89.07&lt;sup&gt;b,1&lt;/sup&gt;</td>
</tr>
<tr>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>-</td>
</tr>
</tbody>
</table>

*MPRT of at least 299 intact particles in each case – except 30% solids and 55 rpm (265 particles), and 40% solids and 55 rpm (267 particles).
Mean values in the same column followed by same letter are not significantly different (p < 0.05) [effect of solid concentration at same rotational speed]
Mean values in the same row followed by same number are not significantly different (p < 0.05) [effect of rotational speed at same solid concentration]

Table 5.7 - Mean normalized particle residence time* (MNPRT) based on the product mean residence time of 94 s - the effect of concentration of solids and the rotational speed of the agitators

<table>
<thead>
<tr>
<th>Concentration of solids (% v/v)</th>
<th>Rotational speed of agitators (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
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<tr>
<td>30</td>
<td>0.964</td>
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<td>40</td>
<td>0.968</td>
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<td>50</td>
<td>0.986</td>
</tr>
<tr>
<td>60</td>
<td>0.948</td>
</tr>
<tr>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>-</td>
</tr>
</tbody>
</table>

*MNPRT of at least 299 intact particles in each case – except 30% solids and 55 rpm (265 particles), and 40% solids and 55 rpm (267 particles).
<table>
<thead>
<tr>
<th>Concentration of solids (% v/v)</th>
<th>Rotational speed of agitators (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>187</td>
</tr>
<tr>
<td>40</td>
<td>188</td>
</tr>
<tr>
<td>50</td>
<td>144</td>
</tr>
<tr>
<td>60</td>
<td>125</td>
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<tr>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.8 - Maximum particle residence time (MXPRT) in seconds - the effect of concentration of solids and the rotational speed of the agitators

<table>
<thead>
<tr>
<th>Concentration of solids (% v/v)</th>
<th>Rotational speed of agitators (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
</tr>
<tr>
<td>30</td>
<td>1.989</td>
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<tr>
<td>40</td>
<td>2.000</td>
</tr>
<tr>
<td>50</td>
<td>1.532</td>
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<tr>
<td>60</td>
<td>1.330</td>
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<tr>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.9 - Maximum normalized particle residence time (MXNPRT) based on the product mean residence time of 94 s - the effect of concentration of solids and the rotational speed of the agitators
CHAPTER 6

CONCLUSIONS

Ohmic heating offers an attractive alternative for continuous sterilization of foods containing particulates because it heats simultaneously both the phases of the liquid-particulate mixtures by internal energy generation. The critical property affecting energy generation is the electrical conductivity of the food material. Electrical conductivity of the selected solid foods increased linearly with temperature. Fruits were less conductive than meat samples. Lower electrical conductivity was observed for porous materials like apples. Lean muscle cuts were much more conductive compared to the separable fat. Within the lean muscle cuts no relationship could be observed between the measured electrical conductivity and the lean muscle fat content. Marbling (fat distribution) may be the important factor affecting the electrical conductivity in lean muscle cuts.

In low-acid foods containing solid particulates like chicken chowmein the sauce was more conductive than all the solid components. By blanching the solids in highly conductive sauce it was possible to increase their ionic content and hence their electrical conductivity. Product containing pretreated solids heated more uniformly during ohmic heating. Sensory test results suggested that the blanching pretreatment did not compromise the quality of the product. Following pretreatment, it may be possible to
uniformly heat the entire product during ohmic heating, thus, preventing thermal abuse and improving the product quality.

Fick’s law can be used to describe sodium chloride diffusion in vegetable tissues like Chinese water chestnut (CWC). The apparent diffusion coefficient increased significantly with temperature. Simulation studies showed that after blanching the CWC disc for 90 s (which was the blanching time required to match its conductivity to that of the sauce), salt diffused only to the small depth from the surface and equilibration time is much higher. So even though concentration and electrical conductivity is not uniformly distributed throughout the solid it is possible to increase the overall ionic content and electrical conductivity of the solid and heat it more rapidly during ohmic heating.

Residence time distribution (RTD) studies is necessary for the determination of the fastest-moving particle for food safety consideration, and the determination of the average and slowest-moving particle for food quality consideration. The residence times and RTD of solid potato particles in starch solution were determined using Radio Frequency Identification (RFID) technique. The effect of solid concentration and the rotation speed of the agitators on the RTD were studied. Mean particle residence time increased with the rotational speed, and no particular relationship was observed between the measured mean particle residence time and the solid concentration. The velocity of the fastest particle was 1.62 times the bulk mean product velocity which is important for food safety design considerations.
LIST OF REFERENCES


