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OHMIC HEATING OF VISCOUS LIQUID FOODS

by

MICHÈLE MARCOTTE

Department of Food Science and Agricultural Chemistry
Macdonald Campus of McGill University
Sainte-Anne-de-Bellevue, Québec, Canada

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DEDICATION

À Slobodan Levi, mon conjoint, et à mon fils, Simon Levi

pour leur patience exemplaire et leur support exceptionnel

au cours des longues heures passées dans la préparation de cette thèse

À mes parents extraordinaires qui ont toujours crû en moi

À Véro, ma tante, qui m'a toujours encouragé à me dépasser

"C'est une leçon que vous devriez observer :
Essayez, Essayez, Essayez encore.
Si tout d'abord, vous ne réussissez pas,
Essayez, Essayez, Essayez encore !"

W.-E. Hickson

ABSTRACT

The technical feasibility of ohmic heating was evaluated for viscous liquids in static ohmic heating cells in three stages. First, electrical conductivities and time/temperature profiles were measured and compared for selected hydrocolloids (carrageenan, gelatin, pectin, starch and xanthan) in water at various concentrations (1-6 %). Of the thickening agents examined, carrageenan gave the highest value for electrical conductivity and the shortest time to raise the temperature from 20 to 100 °C. It was followed by xanthan. Pectin and gelatin samples were found to exhibit lower, but similar electrical conductivities and heating profiles. Starch samples had the lowest electrical conductivity and the temperature of starch solutions never exceeded 62 °C within the specified time limit of 10000 s. The observed ohmic heating behaviour of hydrocolloid solutions corresponded well with their electrical conductivity values. Heating was found to be uniform throughout samples for carrageenan, pectin (1-3 %) and gelatin samples. For xanthan and starch solutions, some non-uniformity in temperature profiles was observed. The homogeneity of heating was related to rheological properties of hydrocolloid solutions and their behaviour at high temperatures. Major differences were found to be attributed to the ash content of charged hydrocolloid powders. Regression equations were established for each type of hydrocolloid solutions revealing a strong interaction between concentration and temperature on electrical conductivities.

In the second stage, the effect of salt and acid concentration was evaluated on electrical conductivities and time/temperature profiles of the above selected hydrocolloids in water solutions at a concentration necessary to achieve a similar apparent viscosity of 0.2 Pa.s at 300 s^{-1} and 20 °C (carrageenan 1.7 %, pectin 2.5 %, starch 4.3 % and xanthan 2 %). At low salt concentration (0.25, 0.5 and 0.75 %), carrageenan and xanthan took the shortest time to raise the temperature from 20 °C to 80 °C and had the highest electrical conductivity profiles, this was followed by pectin samples. Starch was the least effective, having the lowest electrical conductivity profiles. At the highest salt concentration (1 %), the effect of salt overcame the effect of hydrocolloid type giving similar time/temperature and electrical conductivity profiles for all hydrocolloids. The effect of acid was observed to be negligible.

In the third stage, measurements of electrical conductivities, time/temperature and heating rate profiles were performed applying six voltage gradients (5.26, 7.14, 13.16, 17.86, 21.05 and 25 V/cm), with two electrode cross-sectional surface areas (19.84 and 37.95 cm^2) and the electrodes separated at three specific distances (10.05, 14.33 and 20.01 cm) at 150 V. Applied voltage gradients had a major effect on temperature and heating rate profiles but no effect on electrical conductivities. As the voltage gradient increased, temperature profiles were sharper. Similar temperature profiles were obtained for the same distance between the electrodes even though the cross-sectional surface area of electrodes nearly doubled. Increasing the distance between electrodes was found to have a tremendous influence on the temperature and heating rate profiles. This was further confirmed by the good agreement between experimental data and computer simulations of a simplified theoretical model.

Rheological properties of carrageenan, pectin, starch and xanthan solutions were investigated at various temperatures (20-80 °C) and concentrations (carrageenan 1.5, 1.7 and 1.9 %; pectin 2.3, 2.5 and 2.7 %; starch 3.8, 4 and 4.2 %; xanthan 1.6, 1.8 and 2 %) in the presence of 1 % salt. Both temperature and concentration influenced the rheological properties of solutions. Flow curves were well described by the power law model for starch and pectin. A yield stress was observed for carrageenan at 20 and 40 °C only and for xanthan at all temperatures. Herschel-Bulkley models were employed for these two hydrocolloids. The temperature dependency of the power law parameters (m and n) was modeled using a modified Turian approach. A time dependency was found only for carrageenan and a modified Weltmann model was used to evaluate the effect of time on the apparent viscosity of carrageenan.

Finally, electrical conductivity measurements and rheological properties of starch at 4 % and 1 % salt were used as input to evaluate a theoretical model for the electrical, thermal and flow behaviour in a continuous ohmic heating unit. Time/temperature profiles were recorded at various locations in the continuous ohmic heating unit. These results were compared to the output of computer simulations of a model that was developed to describe the electrical, flow and temperature distribution in the continuous ohmic heating unit. They were found to be in good agreement.

RÉSUMÉ

Une étude de faisabilité technique en trois étapes a été entreprise pour évaluer le chauffage ohmique de solutions d'hydrocolloides dans des cellules statiques. Au cours de la première étape, on a mesuré les conductivités électriques et les profils de temps/température de solutions d'hydrocolloides choisies (carraghénine, gélatine, pectine, amidon et xanthane) à des concentrations variées (1-6 %). On a été démontré que les solutions de carraghénine avaient les conductivités électriques les plus élevées et les temps les plus courts pour élever la température de 20 °C à 100 °C. Puis, ce sont les solutions de xanthane qui ont suivi. Les échantillons de pectine et de gélatine étaient comparables, ayant des conductivités électriques et des profils de températures plus faibles que la carraghénine et le xanthane. Les solutions d'amidon ont démontré les plus faibles conductivités électriques avec une température qui n'a jamais excédé 62 °C même après un temps limite spécifié de 10000 s. Il a été observé que les profils de temps/température des solutions d'hydrocolloides suivaient de près les valeurs de conductivité électrique. On a trouvé que la transmission de chaleur à l'intérieur des échantillons était uniforme pour les solutions de carraghénine, de pectine (1-3 %) et de gélatine alors que celle-ci n'était pas uniforme pour le xanthane et l'amidon. L'homogénéité de la chaleur dans les échantillons était directement liée aux propriétés rhéologiques des solutions et leur comportement à hautes températures. On a établi des équations de régression pour les conductivités électriques en fonction de la température et de la concentration pour chacun des hydrocolloides en tenant compte de l'interaction entre la concentration et la température que l'on a trouvée statistiquement significative.

Au cours de la deuxième étape, on a évalué l'effet d'un ajout de sel et d'acide aux solutions d'hydrocolloides sur les conductivités électriques et les profils de temps/température. Les concentrations d'hydrocolloides ont été fixées pour obtenir une viscosité apparente de 0.2 Pa.s at 300 s $^{-1}$ at 20 °C soit carraghénine, 1.7 %; pectine, 2.5 %; amidon, 4.3 % et xanthane, 2 %. À de faibles concentrations de sel (0.25, 0.5 et 0.75 %), les solutions de carraghénine et de xanthane ont donné les conductivités électriques les plus élevées et les temps les plus courts pour élever la température de 20 °C à 80 °C. Puis, les échantillons de pectine ont suivi. L'amidon était la solution d'hydrocolloide la

moins efficace pour l'élévation de température avec des valeurs de conductivité électrique plus faibles. À la plus forte concentration de sel (1 %), l'effet du sel a surpassé l'effet du type d'hydrocolloides, les solutions exhibant les mêmes profils de temps/température et de conductivités électriques pour tous les hydrocolloides. On a trouvé que l'effet de l'acide était présent mais pouvait être négligé.

Dans la troisième étape, on a mesuré les conductivités électriques, les profils de temps/température et les taux de chauffage en fonction de gradients de voltage variés (5.26, 7.14, 13.16, 17.86, 21.05 et 25 V/cm), deux surfaces d'électrodes (19.84 et 37.95 cm^2) et trois distances entre les électrodes (10.05, 14.33 et 20.01 cm). On a trouvé que les gradients de voltage avaient un effet majeur sur les profils de temps/température mais aucun effet sur les conductivités électriques. Lorsque le gradient de voltage était augmenté, les profils de température devenaient plus raides. Des profils de temps/températures similaires ont été obtenus pour une distance semblable entre les électrodes même si la surface des électrodes a doublé. Toutefois, on a trouvé que l'augmentation de la distance entre les électrodes avait un effet très important sur les profils de température et les taux de chauffage. Le tout a été confirmé par l'accord entre les données expérimentales obtenues et les simulations par ordinateur d'un modèle théorique simplifié pour le comportement thermique.

Les propriétés rhéologiques des solutions de carraghénine (1.5, 1.7 et 1.9 %), de pectine (2.3, 2.5 et 2.7 %), d'amidon (3.8, 4.0 et 4.2 %) et de xanthane (1.6, 1.8 et 2 %) ont été mesurées en fonction des concentrations et des températures variant de 20 °C à 80 °C en présence de 1 % de sel. Il a été observé que la température et la concentration avaient une influence importante sur la rhéologie de ces solutions. Les courbes de contraintes de cisaillement en fonction des taux de cisaillement des solutions de pectine et d'amidon étaient bien décrites par le modèle de la loi puissance (Ostwald-de-Waele) alors que pour les solutions de xanthane à toutes les températures et la carraghénine à 20 °C et 40 °C, une contrainte minimale a été observée. Pour ceux-ci, il a donc fallu utiliser le modèle de Herschel-Bulkley. On a évalué l'effet de la température sur les paramètres rhéologiques m (coefficient de consistance) et n (indice de comportement du fluide) en utilisant l'approche de Turian modifiée. De plus, on a utilisé un modèle de Weltmann

modifié pour déterminer l'effet du temps sur la viscosité apparente des solutions de carraghénine.

Enfin, les valeurs de conductivités électriques et des propriétés rhéologiques de l'amidon à 4 % avec 1 % de sel ont été utilisées comme données d'entrée pour tester un modèle théorique décrivant la distribution du champs électrique, le transfert de chaleur et de quantité de mouvement dans une colonne de chauffage ohmique en continu. Pour valider le modèle, les profils de températures ont été enregistrés à plusieurs endroits dans la colonne de chauffage ohmique. Lorsque l'on a comparé les résultats des simulations sur ordinateur et les données expérimentales, on a trouvé qu'elles étaient similaires.

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CLAIMS OF CONTRIBUTION TO KNOWLEDGE

The objective of this study was to evaluate the technical feasibility of ohmic heating for viscous liquids in static and continuous units and to model electrical conductivities, the electric field distribution, the heat transfer and the flow behaviour.

1. Static ohmic heating cells and a continuous ohmic heating unit were designed, constructed, assembled and installed at the Food Research and Development Centre of Agriculture and Agri-Food Canada under the supervision and the technical guidance of Ohio State University (Dr. S.K. Sastry) and McGill University (Dr. H.S. Ramaswamy).

2. A thorough investigation of the different factors related to formulations of hydrocolloid solutions influencing the measurement of electrical conductivities and the ohmic heating behaviour in a static unit was undertaken. It was demonstrated that the choice of hydrocolloids will influence electrical conductivity values and ohmic heating behaviour. Regression equations were established for each type of hydrocolloid solution revealing a strong interaction between concentration, temperature and electrical conductivity values. Major differences between hydrocolloid types on electrical conductivities were mainly attributed to their ash content. Heating was found to be uniform throughout samples for carrageenan, pectin and gelatin samples. For xanthan and starch solutions, some non-uniformity in temperature profiles was observed. The observed ohmic heating behaviour of hydrocolloid solutions corresponded well with their electrical conductivity values. The homogeneity of heating was related to rheological properties of hydrocolloid solutions and their behaviour at high temperatures.

3. As salt and acid were added to solutions of selected hydrocolloids, it was found that the effect of salt clearly dominated the effect of pH. Below 1 % salt, an interaction was found between hydrocolloid type and salt concentration on electrical conductivites and time/temperature profiles. At 1 % salt, all hydrocolloids in

solutions behaved similarly in terms of having same electrical conductivities and time/temperature profiles.

4. Physical parameters (e.g. voltage, distance between and cross-sectional surface area of electrodes) were varied to study their effect on electrical conductivity values, time/temperature profiles and heating rate profiles. These parameters had no effect on electrical conductivity. Voltage gradients had a major effect on the time/temperature and heating rate profiles. It was necessary to apply a mimimum voltage gradient of 15 V/cm in order to obtain the same heating efficiency as in conventional thermal processing in cans with the exception of xanthan solutions due to their high stability for viscosity at high temperatures. Increasing the cross-sectional surface area between electrodes had a negligible effect on time/temperature profiles but, increasing the distance between electrodes had a major impact on time/temperature profiles. Currents were found to limit the application of ohmic heating as in some conditions 10-12 A was quickly attained.

5. A theoretical model was introduced to describe time/temperature and heating rate profiles in a static system. Experimental time/temperature profiles and heating rates were found to be in good agreement with theoretical ones. Therefore, the model could be used to simulate other conditions and establish design criteria for static cells.

6. Rheological properties were measured and compared for selected hydrocolloids in solution at a similar apparent viscosity of 0.2 Pa.s at 20 °C. The power law model was found to accurately describe these properties. Yield stresses were observed for xanthan at all selected temperatures and for carrageenan only at 20 and 40°C. Concentration, temperature and shear rate effects were different depending on the type of hydrocolloids. Apparent viscosities of xanthan were mostly affected by shear rates. A minor effect of temperature was observed. The concentration effect was more important for starch and carrageenan than for pectin and xanthan.

7. A theoretical model was proposed to describe the electrical field distribution, the flow behaviour and the heat transfer during ohmic heating of hydrocolloid solutions in a continous unit. Electrical conductivity data generated in static cell experiments and measured rheological properties were used as inputs for the model. The model was validated experimentally using solutions of starch (4 %) and 1 % salt at various conditions of voltage gradients and flowrates. A good agreement was observed between experimental data and computer simulations.

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CONTRIBUTION OF AUTHORS

The role of different authors are as follows. Michèle Marcotte is the Ph. D. candidate who planned, conducted experiments, analysed results and wrote manuscripts for scientific publication. Hosahalli Ramaswamy is the thesis supervisor who guided the graduate student, corrected, edited and reviewed manuscripts. Gabriel Piette offered scientific advice and cooperation and also reviewed manuscripts. Ali Taherian assisted in analyzing the data on rheological properties. Maher Trigui assisted in gathering experimental data and helped in developing the theoretical model.

NOMENCLATURE

A	surface area (cm^2)
A_i	surface area of each particle (m^2)
A_1	parameter for the Turian equation for m, the consistency coefficient (1/K)
A_2	parameter for the Turian equation for n, the flow behaviour index (1/K)
B_1	parameter for the Weltmann model, ordinate at origin (Pa)
B_2	parameter for the Weltmann model, slope (1/min)
β	coefficient of expansion (kg/m^3 K)
C	concentration (% w/w)
C_p	specific heat (J/kg- °C)
COP	coefficient of performance (dimensionless)
E	voltage gradient or local electric field intensity (V/cm)
E_a	activation energy (kJ/mole)
EE	electric energy consumption (J)
El	electrical characteristic number (dimensionless)
$E(t)$	E-function for RTD
ε	overall energy efficiency (dimensionless)
$F(t)$	F-function for RTD
F_o	accumulated lethality (min)
g	gravitational acceleration (m/s^2)
HE	heating energy (J)
I	current (A)
J	current density (A/m^2)
h	heat transfer coefficient (W/m^2K)
k	thermal conductivity (W/m °C)
$K_{C,25}$	concentration constant at 25°C (S/m %)
K_S	solid constant (1/ %)
K_T	temperature constant (S/m °C)
K_{TC}	temperature and concentration constant (S/m kg K)
K_{TS}	Sastry's temperature constant (1/ °C)
L	distance between electrodes (cm)

λ	latent heat of evaporation (J/kg)
m	mass flow rate (kg/s)
m	consistency coefficient (Pa.s $^{n-1}$)
M	mass of product (kg)
μ	viscosity (Pa.s)
n	flow behaviour index (dimensionless)
$\vec{n}$	vector
η	apparent viscosity (Pa.s $^{-1}$)
p	hydrostatic pressure (Pa)
P	power (W)
φ	phi-direction
ψ	viscous dissipation (J/m^{2}s)
q''	energy generation rate (J/m^2 s)
q_p	energy transferred to particles (J/m^2 s)
q_r	radiative heat transfer (J/m^2 s)
$\dot{Q}$	volumetric heat generation (W/m^3)
Q_p	dimensionless volumetric heating term
r	radius (m)
r^2	coefficient of determination
R_o	radius of the cylinder (m)
R	resistance (ohm)
RT	residence time (s)
$\mathcal{R}$	gas constant (8.3184 x 10^{-3} kJ/mole K)
ρ	density (kg/m^3)
S	surface (m^2)
S_a	axial stratification (K/m)
SEH	specific heating energy (J/kg)
SEE	specific electric energy (J/kg)
Slope	slope of a linear equation

σ	electrical conductivity (S/m or 1/ohm*m)
$\bar{\sigma}$	average electrical conductivity (S/m or 1/ohm*m)
t	time (s)
T	temperature (^{o}C)
θ	theta-direction
τ	shear stress (Pa)
$\dot{\gamma}$	shear rate (s^{-1})
U	heat transfer coefficient to the surroundings (W/m^2 K)
v	velocity (m/s)
$\dot{v}$	volumetric flow rate (m^3/s)
V_f	volume of fluid (m^3)
V_i	volume of each particle (m^3)
V	voltage (V)
X_1	parameter for the exponential oncentration effect (1/ %)
X_2	parameter for the power concentration effect (1/ %)
Z	slope of the logarithmic thermal death time (^{o}C)

Subscripts

a	apparent
a	above 0 ^{o}C
above	above 0 ^{o}C
acc	accumulated
ap	apparent
b	below 0°C
below	below 0°C
bf	below freezing
C	concentration
e	equilibrium
f	fluid
fish	fish

fp	freezing point
fp	fluid to particle
i	each
in	inlet
l	liquid
latent	latent
m	mean
min	minimum
max	maximum
o	reference
out	outlet
p	particle
ref	reference
r	radial direction
ra	radiative
s	surface
T	temperature
total	total
0	at a reference temperature of 0°C
25	at a reference temperature of 25°C
in	inlet
out	outlet
w	wall
water	water
z	z-direction

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Thermal processing is the most common unit operation in the food industry to preserve food systems and extend shelf life since the development of the batch sterilisation technique by Nicolas Appert in the 19th century. In the past few decades, one of the major developments in food processing has been the continuous high temperature short time sterilisation process, largely driven by the industry interest in increasing the speed of production while satisfying consumers demand for superior quality food products (Holdsworth and Richardson. 1989). As a result. aseptic processing technology, a rapid and continuous thermal treatment. has progressively replaced conventional in-can sterilisation for liquid foods (e.g. fruit juices and dairy products).

Liquid foods of various viscosities are being continuously thermally processed using plate and frame. tubular or scraped surface heat exchangers. It has been recognised that aseptic processing of low-acid heterogeneous liquids containing large particles is more difficult due to mechanical damage as a result of blade scraping and unknown residence time distribution. The formation of a deposit at the heating surface has been observed to occur. With these systems. the size of particles is limited to 10-15 mm and only a low proportion of solids in the liquid (less than 30%) is efficiently processed because heat must first be transferred from the heating surface to the liquid before it can reach the particle. Moreover, the temperature of the liquid can be easily monitored but it is impractical to obtain the temperature at the centre of the particle without interfering with the process. This necessitates overcooking of liquid to ensure that the particles receive enough heat to be commercially sterile. Therefore, the application of aseptic processing to low-acid foods containing particles is limited by the time required for the centre of the particle to heat sufficiently. Furthermore, this must be proven to the appropriate regulatory agencies as outlined by Dignan *et al.* (1989). Only recently i.e. in May 1997, aseptic processing of a low acid liquid food containing particulates (e.g. potato soup) has been approved by the Food and Drug Administration (FDA) in the

United States of America (USA). The methodology has been described in detail by Palaniappan and Sizer (1997).

Currently, non-traditional rapid methods of heating, involving new uses of electricity, are being developed to replace conventional heating systems. One promising solution to overcome the problems associated with aseptic processing is ohmic heating. This method relies on direct resistive heating which occurs when an alternating current is passed through the food. The food is made part of an electrical circuit. Heat generation takes place volumetrically within the food because of its inherent electrical resistance. It offers an alternate way to rapidly heat food. Moreover, it can be applied to solid foods. Typically, heating rate in the region of 1-10 °C/s are observed. It is possible to obtain a temperature rise in food of 100 °C with a residence time between 10-100 s in commercial applications (Skudder, 1988). Several authors (de Alwis *et al.*, 1989; Sastry and Palaniappan, 1992a) have demonstrated that it is even possible in using ohmic heating to heat the centre of the particle faster than the liquid. Therefore, ohmic heating of liquids containing particulates could be regarded as an aseptic process of homogeneous liquids, which requires only the monitoring of the liquid temperature (Larkin and Spinak, 1996).

The benefits of ohmic heating are numerous (Biss *et al.*, 1989; Skudder and Biss, 1987). Heating is rapid and uniform. It is comparable to microwave heating without an intermediary step of converting electricity into microwaves before heating and, unlike microwave heating, the depth of heat penetration is virtually unlimited. A large temperature gradient is usually not experienced within the food. The process is ideal for shear-sensitive products. Particles are handled more gently and maintain their integrity. A high percentage of solids in liquid (50-80 %) can be accommodated. The ohmic heater assembly can be seen in the context of a complete product sterilisation or cooking process where there is already a holding tube assembly, pumping and cooling systems.

The design of a continuous ohmic heating column is principally determined by the selected configuration of the system, the heating rate, the flow rate and the desired temperature rise of the food product (Reznik, 1996). The ohmic heating rate is calculated from the electric field, the electrical conductivity, the density and the specific heat of the food product. Therefore, the heating rate depends largely on the physical properties of the food, more specifically on the electrical conductivity (de Alwis and Fryer, 1992).

Ohmic heating works because most pumpable foodstuffs contain dissolved ionic salts, acids and water in excess of 30 %, which render the material electrically conductive. Pure fats, oils, alcohols and sugars are not suitable materials for ohmic heating. These substances are not sufficiently electrically conductive. Very little reliable data on electrical conductivities, in the context of ohmic heating, have been published and there is a great deal of discrepancy in experimental values (Halden *et al.*, 1990; Mitchell and de Alwis, 1989; Palaniappan and Sastry, 1991a). Usually, the electrical conductivity of liquids is measured at room temperature, which is not the temperature experienced by the food during ohmic heating. Electrical conductivity is extremely dependent on the frequency of the AC voltage applied. Data have been published for high frequency processes (e.g. microwave) but they are not applicable to low frequency ohmic heating processes. It is generally observed that electrical conductivity of liquids is higher than that of solids although only few publications have reported on electrical conductivities of liquid foods (Palaniappan and Sastry, 1991b). The effect of temperature on electrical conductivity is clear both for liquid and solid food materials. As temperature increases electrical conductivity increases. In liquid foods, the effect of the proportion of solids is of less importance but still significant. As the percentage of solids increases (except for salt) the electrical conductivity decreases.

Considerable effort has gone into finding suitable models to understand the complex ohmic heating process of liquids containing particulates either in a static heater or in a continuous unit. A full model of the ohmic process requires a simultaneous solution of the electrical, flow and thermal differential equations in the geometry of the ohmic heater (Sastry and Li, 1993). Coupled electrical, momentum and thermal equations are solved numerically, usually using the finite element method to obtain the temperature distribution. The finite element method is preferred when handling complex geometries. Two major groups are working on the modelling of ohmic heating: one from Ohio State University (Sastry's group) the other from Cambridge, now Birmingham, (Fryer's group). Similar assumptions are used for the flow and enthalpy balance but an alternative approach or circuit analogy for a multiparticle system is used (Sastry's group) rather than solving the Laplace equation for the electric field distribution (Fryer's group) to reduce computer time. As a result of various simulations, it has been found that the electrical conductivity of solid particles and carrier liquid should be closely matched for the heating rate to be similar. Generally, ohmic heating would be more efficient with a high ratio of solid particles to liquid which is not the case in conventional aseptic processing. Particle orientation (either parallel or perpendicular) in the field as well as irregularly shaped particles were observed to strongly influence the heating rate of the particle in the liquid (de Alwis *et al.*, 1989; Sastry and Palaniappan, 1992b). Particle size, heat transfer coefficient and residence time distribution of particles have been found to be less important than in conventional aseptic processing. Ohmic heating of liquids has not been studied as much as ohmic heating of heterogeneous mixtures of liquids and solids. Moreover, data on the electrical conductivity of viscous liquids used as carrier fluids in low-acid foods containing particles are scarce. Since little has been published on the subject and a variety of hydrocolloids are available to design specific food formulations, the following objectives were proposed for the present study:

1) To determine electrical conductivities of selected hydrocolloids in solutions under ohmic heating conditions (i.e. using low voltage alternating current);

2) To evaluate the ohmic heating behaviour of selected hydrocolloids in solutions i.e. the determination of the temperature distribution;

3) To study the effect of other ingredients such as salt and citric acid on electrical conductivities and ohmic heating behaviour of selected hydrocolloids in solutions;

4) To evaluate the importance of several parameters affecting the measurement of electrical conductivities and ohmic heating behaviour in static cells;

5) To characterise the rheological behaviour of selected hydrocolloid solutions;

6) To model the electrical, flow and the thermal behaviour of hydrocolloids in solution during ohmic heating in a continuous unit and to validate the model experimentally.

In order to achieve these objectives, both various static ohmic heating cells and a continuous pilot plant ohmic heater were constructed. They were installed under the technical supervision of Ohio State University at Agriculture and Agri-Food Canada's Food Research and Development Centre (FRDC) in St. Hyacinthe, where the research was carried out.

CHAPTER 2

LITERATURE REVIEW

THERMAL PROCESSING VS. OHMIC HEATING

Thermal processing is the most common unit operation used to stabilise food systems. Heating processes are either batch or continuous depending mainly on the state of the food. Batch treatments are commonly used for heating solids while both batch and continuous processes are used for liquid foods or liquids containing solid particles. Traditionally, batch-heating treatments were first developed and applied to both solid and liquid foods. In-container sterilisation is still the basis of a large-scale industry but in a modern food processing plant, the overall manufacturing practice tends to be oriented towards continuous operations, particularly for liquid foods or mixtures of liquid containing particles.

The aseptic processing technology was introduced as a form of continuous and rapid thermal treatment to solve problems associated with the conventional "in-container" sterilisation of foods (e.g. low rate of heat penetration to the cold spot, long processing times required, destruction of nutritional and sensory attributes, low productivity and high energy costs (Mitchell, 1987; Smith *et al.*, 1990). It is defined as a high temperature/short time process that requires four distinct and successive operations to be carried out in a closed sterile environment: 1) continuous product sterilisation under appropriate quick heating, holding and cooling; 2) package sterilisation independent of product sterilisation; 3) aseptic filling of the cooled sterile product into sterile packages at ambient temperature and finally, 4) aseptic sealing of packages (Woodroof, 1990). Aseptic processing of homogeneous liquids has progressively replaced conventional in-can sterilisation in Canada and the United States of America (USA) since the full approval for the use of hydrogen peroxide as a sterilant for packaging materials by the Food and Drug Administration (FDA) in February 1981. This allowed low temperature sterilisation, using 35 % hydrogen peroxide, for packaging materials.

In 1989, aseptic processing and packaging was recognised by the Institute of Food Technologists (IFT) as the most significant innovation in food processing during the last 50 years. The advantages of aseptic processing are numerous. A superior quality product is usually obtained because the bactericidal effect of a thermal treatment increases at a greater rate than chemical changes as the temperature increases (Holdsworth and Richardson, 1989). Heat transfer to the food is faster and more uniform. Therefore, there is a potential for energy savings. The process is highly efficient because it is continuous. Lower cost packages can be used as they do not need to be exposed to high sterilisation temperatures.

In aseptic processing, most continuous heating techniques are indirect although direct steam injection or steam infusion is used for shear sensitive higher viscosity foods or products that are susceptible to fouling. Therefore, they rely on conductive, convective and radiative mechanisms to transfer heat from the heating medium to the food material. With indirect heaters, condensing steam is used as an external medium to supply the heat for sterilisation. For homogeneous liquid foods of low viscosity (e.g. milk), plate and frame heat exchangers are normally used. A tubular heat exchanger is generally selected either for heating or cooling medium viscosity liquids (e.g. ice cream mixes, sauces, fruit purees) and liquids containing particulates up to 10 mm. For highly viscous liquids, with/without particles, heating is usually performed using scraped surface heat exchangers (SSHE). A proportion of up to 40 % w/w solids can be processed. Products processed in this category are jams, puddings, and prepared meals such as sauces or viscous soups containing meat, vegetables and/or pasta particulates.

Presently, it is difficult to apply aseptic processing for low-acid heterogeneous viscous liquids containing large particles. In conventional aseptic heating, Parrot (1992) demonstrated that it is not possible to sterilise particulate foods at temperatures much above 130 °C without serious overheating of the liquid phase. Mechanical damage as a result of blade scraping is often observed. The formation of a deposit at the heating surface is known to occur even if there is the preventative action of blade scraping. With these systems, the size of the particles is limited to 10-15 mm and a low proportion of solids in the liquid (less than 30 %) is required since heat is transferred from the heating surface to the liquid first before it can reach the particle. The temperature of the liquid can be easily monitored but it is almost impossible to gather the temperature at the centre of the particle without interfering with the heating process. Overcooking of the liquid becomes necessary in order to ensure that particles have received sufficient heat to be commercially sterile. In conventional aseptic processing, the coldest point of the system is the centre of the fastest and largest travelling particle. Conduction, a slow heating process, is the main heat transfer phenomenon within the particle. Therefore, the application of High Temperature Short Time (HTST) technologies to particulate foods is limited by the time required for the centre of the particle to heat up sufficiently. The approval of an aseptic process for low-acid liquids containing particulate by the FDA (Dignan *et al.*, 1989) requires the selection of the sterilising value and the development of a conservative model to predict the fastest particle's centre temperature by the time it reaches the end of the holding tube. A reasonable value for the heat transfer coefficient between the liquid and the particle should be used. Detailed studies of residence time distribution of the particles in liquids are required. Experimental data on quantitative microbiology must be provided to validate the process. This complicated procedure for aseptic processing was filed to the FDA in the USA for potato soup (low acid particulate food) and approved in May 1997 (Palaniappan and Sizer, 1997). A workshop to discuss concerns, which needed to be resolved to develop aseptic processes for particulate foods, was organised in 1997 (Larkin, 1997). Details are given in four publications by Sastry (1997), Marcy (1997), Digeronimo *et al.* (1997) and Damiano (1997).

Since the 1980's, ohmic heating has been seen as a promising development to solve problems encountered in aseptic processing of low acid liquids containing particulates. Several authors (de Alwis *et al.*, 1989; Sastry and Palaniappan, 1992a) have demonstrated that in ohmic heating, it is possible to heat the centre of the particle faster than the liquid. Therefore, the cold spot of the particle is located at the surface. From a legislative point of view (Larkin and Spinak, 1996), ohmic heating of the liquids containing particulates becomes a special condition. If it can be proven that the temperature at the centre of all particles during ohmic heating is always greater than that of the liquid at the inlet of the holding tube then the calculated process time is simplified as for the establishment of an aseptic process of homogeneous liquid using only the temperature of the liquid at the inlet of the holding tube. Biological validation may not be required to establish the process but only to verify it. Table 2.1 lists some experimental and regulatory milestones that have marked the development and implementation of APV ohmic heating installations throughout the world.

ADVANTAGES OF OHMIC HEATING

Recent R&D in continuous thermal processing of foods has been mainly driven towards assessing the technical feasibility of new and rapid methods, based on the use of electric energy. It is worth noting that advanced food processing techniques such as microwave, radio-frequency and ohmic heating can be used as rapid heating techniques for solid and liquid foods.

Ohmic heating occurs when an alternating current is passed through a food (Skudder and Biss, 1987) that is electrically conductive. Heat generation takes place volumetrically. The electrical energy is directly converted into heat causing a temperature rise. This system is comparable to an electrical circuit, which is comprised of a resistance and a source of voltage and current. The food product acts as the resistance when placed between two electrodes and the current passes through it. In other words, the food is made part of an electrical circuit. Other synonyms are used in the literature to describe this principle of heating: direct resistance heating, Joule effect heating, electroconductive heating and electroresistive heating. Classical heat transfer mechanisms such as convection or conduction are minimal. It offers an alternate way to rapidly heat food, bypassing conventional heating systems. Other direct volumetric heating techniques are also available and were classified in three categories by Pain *et al.* (1995): steam (e.g. injection and infusion), radiation (e.g. infrared, microwave and radio frequency) and Joule Effect in which ohmic heating is found. Ohmic heating is *comparable* to microwave heating without an intermediary step of converting electricity into microwaves through the magnetron before heating the product.

The benefits of ohmic heating are numerous (Biss *et al.*, 1989). The most important is that heating is very rapid. A large temperature gradient is not experienced

Table 2.1 Milestones in the commercial development and implementation of the APV ohmic heating technology for fluids containing particulates

Date	Events
1980	UK patent for electrode assembly to Electrical Council Research at Capenhurst (ECRC) in UK
1983	US Patent for electrode assembly to ECRC
1983	Exclusive international exploitation license given to APV from ECRC
1988	Food Processing Award in UK
1989	Start-up of the first industrial unit in UK
1990	Du-Pont Award in US Du-Pont Diamond Award in US
1991	Power for Efficiency and Productivity Price in UK
1991	Eta Price from International Union of Producers and Distributors of Electrical Energy
1991	Approval of APV ohmic heating technology for the production of ambient stable low acid ready meals in the UK
1992	First US based ohmic-aseptic system installed at the Advanced Food Science (AFS) at Land O'Lakes
1993	FDA in the United States approved the ohmic heating technology for low acid fluids containing particulates
1993	Royal Society Esso Energy for the best energy utilisation
1995	Approval of the APV ohmic heating technology for the production of high acid fruit products for institutional use in the UK
1996	APV received the Industry Achievement Award from IFT

within the food i.e. heating is uniform. The process is ideal for shear-sensitive products. Ohmic heating has the ability to heat the food continuously without the need of the hot heat transfer surface of a SSHE or a tubular heat exchanger that may foul. Using an ohmic heater, particles are handled more gently and maintain their integrity when compared with a SSHE. The process is quiet in operation due to the absence of rotating parts in the system. In addition, a high percentage of solids in liquid (50-80 %) can be processed. Unlike microwave heating, the depth of heat penetration in the food is virtually unlimited. A high level of control and automation ensures safety during the operation. Finally, it is easier to tailor a heating time/temperature profile to ensure sterility because heat is generated within the solids without the reliance on thermal conductivity through the liquid.

The ohmic heater assembly can be seen in the context of a complete product sterilisation or cooking process where there is already a holding tube, pumping and a cooling systems. The ohmic heater replaces the SSHE in an aseptic processing line, as shown in Figure 2.1. In this case, an ohmic heating column consisting of 4 electrodes would replace the conventional SSHE. The food product is fed vertically from the bottom to the top of the column. Heating occurs in three sections between two electrodes. The food is then held in the holding tube for temperature equilibration between the liquid and solid. It is cooled in tubular heat exchangers before being packed in an aseptic environment. Commercial APV ohmic heating installations are available for different production throughput. As an example, a 30 kW unit is needed to process up to 300 kg/h and 75, 125, 300 and 600 kW units are used for 750, 1250, 3000 and 6000 kg/h of product, respectively. For laboratory experiments, a 5 kW unit is used for a single batch of 50 kg or it can be operated in a continuous mode of 50 kg/h. The power for pilot scale units is 10 kW for a continuous production of 100 kg/h. This particular ohmic heating technology for particulate foods was first developed by the Electrical Council Research in Capenhurst, England. It was licensed to APV Baker Ltd for commercial exploitation of the results. APV has patented the electrode assembly in England (Simpson, 1980) and the United States (Simpson, 1983). Over 18 commercial industrial plants were installed, mostly in Europe and Japan and more recently in the USA. Several

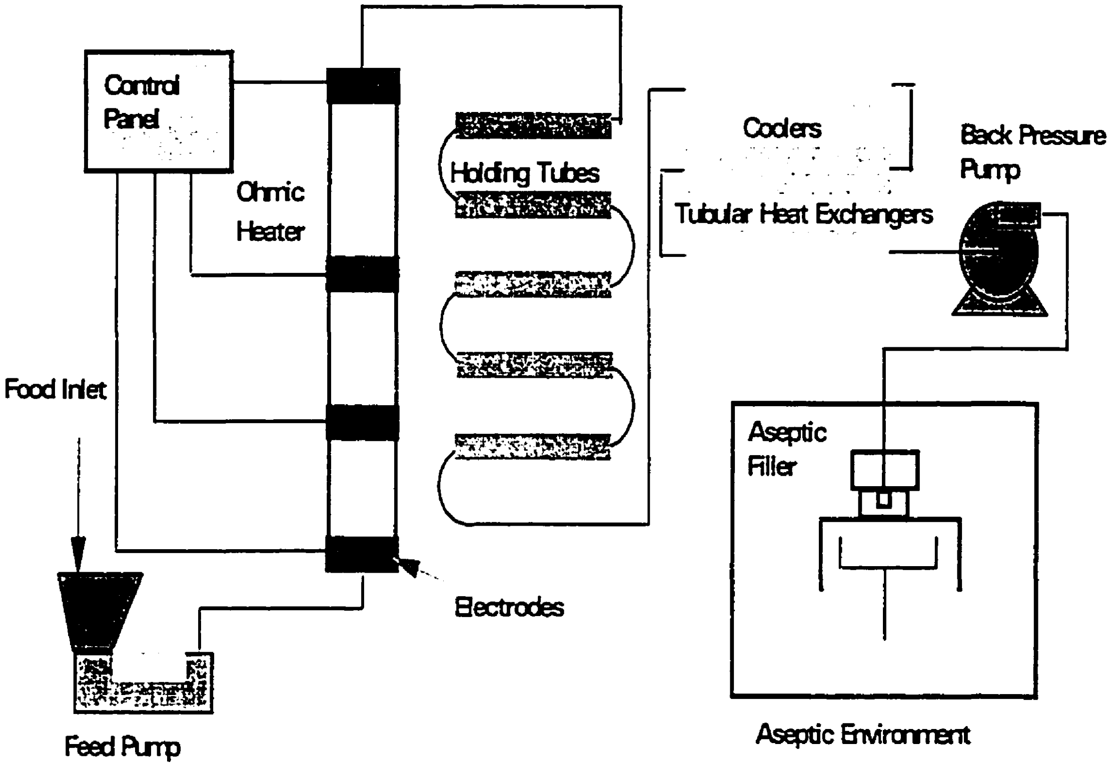


Figure 2.1 An aseptic processing line with an ohmic heater

authors (Taffe, 1987; Frampton. 1988; Swientek, 1988; Grikitis. 1989; Sperber, 1992; Anon., 1994; Rice, 1995; Tjomb, 1995; Pain *et al.*, 1995; Anon., 1996) have reported on the commercial application of the APV ohmic heating technology for particulate foods. Table 2.2 summarises the information and illustrates some examples of commercial ohmic heating units used for laboratory, pilot and industrial applications with food systems.

APPLICATIONS OF OHMIC HEATING

Historical perspective

The concept of ohmic heating technology is not new, early applications date back to 1897 (Jones, 1897). Over the last century, a number of attempts have been made to use this technique in several food processing applications (de Alwis and Fryer, 1990a; Palaniappan and Sastry, 1990). Between the 1950-70's, experiments were performed to use ohmic heating for thawing purposes. Faster thawing rates were observed, but satisfactory results were obtained only if good contact between the food and electrodes was maintained. Problems occurred with complex geometry. Lately, microwave thawing has replaced the technology. Ohmic heating experiments have been performed on cut and peeled potato slices and corn on cob to deactivate enzymes. In fact, an industrial process "OSCO" was developed in the 70's to treat peeled and cut potatoes in solution before frying. Ohmic heating has been used as a rapid heating method for frankfurters, with electrodes spiked at both ends of the sausages. From 1930-1970, rapid heating methods for vending applications were developed for heating sausages, pizzas, and hamburgers. Nowadays, microwaves are used as a more convenient alternative. Early concepts in pasteurisation and sterilisation preceded the introduction of a reliable aseptic packaging technology. Modifications of can designs to include electrodes fixed either temporarily or permanently on containers were used to ohmically sterilise foods. Continuous ohmic pasteurisation was introduced in the USA for the pasteurisation of milk in late 1920's as a successful commercial technique, the "Electro-Pure" process (Anderson and Finkelstein, 1919). In the 1930's, 50 industrial electrical milk sterilisers were in operation but

Table 2.2 **Examples of commercial ohmic heating units for laboratory, pilot scale or industrial applications**

Who	Year	Where	Power	Product
Sous Chef Ltd (H.J.Heinz division)	1989	UK	75 kW	Prepared meals of meat and vegetables (5, 10, 25 l bulk packaging)
Confidential	NA	Europe	75 kW	High acid products such as fruits in syrup and vegetables and meats
Confidential	NA	Europe	300 kW	Low acid particulate foods
Advanced Food Science (AFS) Land O' Lakes Minneapolis, IL	1992	US	5 kW	R & D assistance for product development, a continuous system
NCFST/FDA/APV Bedford Park, IL	1994	US	5 kW	Dynamic batch ohmic heating unit for research tests
Nissei Co. Wildfruit Division (1 of 6 ohmic heaters)	NA	Japan	75 kW	High acid particulate foods such as whole strawberries in syrup (10 l units or 10 kg bags in box)
Confidential	NA	Japan	75 kW	Prepared meals
Confidential	NA	Japan	300 kW	High acid particulate foods
Nestlé Food Service Division « Chef Mate brand » Trenton, MO	NA	US	300 kW	Shelf stable low acid beef stew and ravioli in # 10 can packaging
CTCPA Dury-lès-Amiens	1995	France	10 kW	Pilot scale installation. Aseptic tank of 150 l and 20 l bags in box
UTC Compiègne	1990	France	5 kW	Capacity of 1 kg per batch at a laboratory scale
Odin Packaging Systems, Parma	NA	Italy	NA	Testing facilities for a full range of products
EPRI Palo Alto, CA	1996	US	NA	NA

disappeared in the 1950's (Getchell, 1935; Moses, 1938). A review of problems in the early development of the ohmic heating technique was outlined by de Alwis and Fryer (1990a). The problems resulted mainly from improper contact between electrodes and the food product. Electrolysis and product contamination were observed following the use of unsuitable electrode materials. As well, adhesion of product to the electrodes often occurred. The difficulty in ensuring good contact between electrodes for complex solid geometry was the reason for poor experimental results. Before a reliable aseptic packaging technology existed, rapid and continuous sterilisation techniques using ohmic heating were not practical. As with packaging, recent developments in pumping technologies have ensured that particulate foods move without any mechanical damage. This rapid and sophisticated technology requires a level of control only possible through the use of recent computer technology.

Recent applications

The most recent industrial achievement in ohmic heating includes the development of the "ELECSTER" process for the pasteurisation of milk which is based on the "Electro-pure" process and the "APV Baker Ohmic Heating Technology" for the sterilisation of particulate foods (Skudder, 1991). The latter was recently recognised as a commercial breakthrough at the 1996 annual meeting of the IFT. APV Baker Ltd received the Industry Achievement Award (Giese, 1996) for the development of the ohmic heating technology for the sterilisation of fluid containing particles. In France, CTCPA (Centre Technique de la Conservation des Produits Agricoles) and UTC (Université Technologique de Compiègne) joined together to install an APV pilot plant unit to help European food companies in developing sterilisation processes for liquids containing particles in 1995 (Zuber, 1997).

There has been a renewed interest in developing heating (i.e. blanching, sterilising and cooking), thawing or gel forming technologies using the ohmic heating principle. In some cases, it could be as economical as other conventional processes (Allen *et al.*, 1996).

Only recently has considerable attention been given to ohmic heating for the thermal processing of foods due to its rapid and uniform treatment coupled with its high-energy efficiency and technical simplicity. Qihua *et al.* (1993) evaluated the design and performance of an ohmic heating unit for thermal processing of liquid foods. They used a static unit to easily determine electrical conductivities of orange juice. In a newly designed continuous unit, it was found that the outlet temperature and the rapid establishment of a steady state was principally controlled by the voltage gradient and flow rate for given electrical conductivities and other properties of the fluid and inlet temperature.

Mizhrahi (1996) found that ohmic heating might provide an effective method for blanching large vegetables because the process can be accomplished in a relatively short time regardless of the shape and size of the product. Therefore, any need for dicing as commonly performed prior to water blanching could be eliminated. For a similar size vegetable, the extent of solute leaching for ohmic heating and hot water blanching was observed to follow the same pattern and was proportional to the surface to volume ratio of the product and the square root of the process time. Consequently, ohmic heating used for large pieces of vegetables could reduce efficiently the extent of solute leaching.

In France, ADIV (Association pour le développement de l'industrie de la viande) and EDF (Électricité de France) formed an alliance to design, build and evaluate a static ohmic heating unit for processed meats that are pumpable (Peyron, 1996). They found that there was no significant difference between conventional and ohmic heating on the yield, microbiology and sensory evaluation of two products (e.g. pâté de foie et pâté de campagne). However, the ohmic heating time was 10-20 times less than the conventional cooking operation.

Ohmic heating was also reported to be applied to thawing of foods (Naveh *et al.*, 1983). An USA patent was more recently obtained by Ohtsuki (1990) for thawing frozen foods using a three-electrode system with voltages between 5 and 20 kV and a current density range of 0.02-0.3 A/m^2. Traditionally, frozen blocks of fish are thawed by immersion in warm water with the following major disadvantage: requirement of large amounts of fresh water that become wastewater. It also compromises the surface microbial quality of foods as the water temperature is 30 °C. As well, valuable soluble proteins are leached. Early investigations of ohmic heating (Jason and Sanders, 1962ab; Sanders, 1963; Burgess *et al.*, 1967) revealed the appearance of hot spots as enough heat is generated to cook. Even recent experiments (Henderson, 1993) showed that hot spots occur simultaneously on localised regions and could be controlled by the supply of electrical current. Roberts *et al.* (1998) successfully designed and tested a fully automated prototype for ohmic thawing of fish blocks based on the control of the current flow within the product to eliminate the formation of hot spots.

Huang *et al.* (1997) successfully investigated the feasibility of using a batch type ohmic heater to coagulate fish proteins from the frozen fish mince wash water. Ohmic heating was employed as a rapid method of heating and was found to maximise gel functionality in Pacific whiting surimi as compared to conventional heat treatment which allows the product to develop undesirable textural properties as a result of optimal enzymatic activity occurring at 55 °C (Yongwawatdigul *et al.*, 1995a).

Uemura *et al.* (1996b) evaluated a novel continuous ohmic heating process for liquids. A 2-cm diameter tube was used. Ring electrodes were inserted into the wall of the tube and spaced. A constant voltage was applied (20 kHz and 68 V) to the two electrodes. The space between electrodes was found to be the most significant factor influencing the temperature profile. This system is another option that could be used instead of the APV system for liquids.

Another possible application of ohmic heating is in the concentration of fluids. This technique is advantageous for highly viscous products, where fouling might occur. To date, there have been no scientific publications on the subject as applied to food fluids. However, EDF (Aussudre, 1996) has worked on the design of a continuous ohmic heating concentrator for the pulp and paper industry in collaboration with the CTP (Centre Technique du Papier). It has been observed that to be efficient, electrical conductivity values should range between 0.01 to 10 S/m. Electrical conductivities were found to be influenced by the concentration of species in solution. As the concentration was increased electrical conductivities were increased until the concentration reached a certain level after which electrical conductivities dropped. In designing a concentrator, it is crucial to take into account that the electrical conductivity will change with the concentration.

As a rapid method, the ohmic heating principle was also used to design a laboratory apparatus for fat analysis in meat products (Piette and Jacques, 1997).

DESIGN OF AN OHMIC HEATER

Most current commercial ohmic heaters are engineered specifically to interface with a continuous process line. The design of an ohmic heating column is mainly determined by the selected configuration of the system, the heating rate, the flow rate and the desired temperature rise of the food product (Reznik, 1996). Two geometries of ohmic heater are possible: a plate and frame configuration where electrodes are sandwiched between insulating plastic spacers. This is mainly used for electrical treatment of liquid foods. This configuration is also classified as the transverse field mode (Stirling, 1987). The applied electric field and current flux are at right angles to the mass flow. The second is a tubular heating column and is preferred for particulate foods because of its internal clearance since electrodes are inserted into an electrically insulated tube (Skudder, 1988). This configuration is considered collinear, that is the applied electric field and current flux are parallel to the mass flow (Stirling, 1987). These configurations will determine the heating behaviour and the flow pattern.

The local internal electrical heat generation rate at the ohmic heater is calculated using Ohm's law for constant voltage:

$$\dot{Q} = E^2 \sigma \quad or \quad (\nabla V)^2 \sigma \qquad [2.1]$$

Where $\nabla V = E$ is the voltage gradient (V/m) or electric field intensity and σ is the local electrical conductivity. For a constant current situation, the relationship is:

$$\dot{Q} = \frac{|J|^2}{\sigma} \qquad [2.2]$$

Where J is the current density (A/m^2). Most commercial ohmic heaters operate under constant voltage conditions. In the absence of other significant heat transfer mechanisms such as convection or/and conduction, neglecting heat losses to the surroundings and using constant voltage conditions, the heating rate can be calculated:

$$\frac{dT}{dt} = \frac{\sigma (\nabla V)^2}{\rho C_p} \quad [2.3]$$

Typically, high heating rates in the range of 1-10 °C/s are reported. A commercial residence time of less than 10-100 s is possible to obtain a temperature rise in the food of 100 °C (Stirling, 1987). The temperature rise in each section of an APV continuous ohmic heater tube (Skudder and Biss, 1987) can be calculated by Equation 2.4:

$$\Delta T = \frac{V^2 \bar{\sigma} A}{L m C_p} \quad [2.4]$$

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

$$P = m C_p (T_{out} - T_{in}) \quad [2.5]$$

It is recommended that the maximum power at the transformer be 30 % greater than the required power. The current and voltage required to deliver that power are calculated using standard electrical relationships (Equations 2.6-2.9):

$$P = VI \quad [2.6]$$

$$P = RI^2 \quad [2.7]$$

$$P = \frac{V^2}{R} \quad [2.8]$$

$$V = RI \quad [2.9]$$

Limited voltage and current may be applied to the system. Voltages of 12000 V are readily available. Commercially, a 3.3 kV per phase is used and can be easily controlled.

Electrolytic effects

There is less flexibility for the frequency of the alternating current, which usually comes directly from a public utility at 50 Hz or 60 Hz. It is known that electrolysis effects exist at low frequency (50-60 Hz) for DC and also AC current. Many systems have been developed at higher frequencies (100 Hz) to avoid this problem as well as the dissolution of metallic electrodes (Reznick, 1996; Remik, 1988). For AC, the maximum safe current will depend on the current density, a property of the electrode material and geometry. Upon ohmic heating, there is a direct contact between the electrodes and the food itself. Therefore, one may ask if the flow of current through the food induces chemical changes. According to one of Faraday's laws, for a direct current flow, the amount of chemical change resulting from the flow of current across an electrode/solution interface is proportional to the quantity of electricity passed through an electron-transfer process. However, alternating current flow can occur through a non-electron transfer (i.e. without electrolysis) because of the presence of ionic double layers (Crow, 1979) at the interface electrode/electrolyte. Electrostatic alignment of solution ions and the electrode surface of opposite charge is formed similar to a capacitor. Therefore, an alternating current flow occurs by charge migration only. This capacitive double layer can support only a certain maximum alternating current density before a sufficient voltage is reached to produce electrochemical reactions. This maximum safe current density must be determined for the specific electrode material. Stirling (1987) has reported on total faradaic current densities in a platinized titanium-electrode/saturated-sodium chloride cell. Direct chemical analyses (e.g. dissolved oxygen and free chlorine) were used to confirm the results (Stirling, 1987). A safe working maximum of 8000 A/m^2 was deduced with less than 0.1% Faradaic current. It is current practice to use a maximum of 4000-5000 A/m^2 for design purposes.

Surface of electrodes

The surface area of the electrodes is calculated from the required power, the maximum voltage at the transformer and the current density of the electrodes.

Energy efficiency

Huang *et al.* (1997) established a procedure to calculate the energy efficiency of the operation. They determined the specific electric energy (SEE) consumption with heating time (t) for the mass of product (M) as a function of the constant voltage (V) and the varying current (I) measured:

$$SEE(t) = \int_0^t \frac{V\,I(t)}{M}\,dt \qquad [2.10]$$

Assuming that the specific heat of the product remains constant throughout the process, the specific heating energy (SHE) can be calculated:

$$SHE(t) = C_p\,(T(t)-T_0) \qquad [2.11]$$

The overall energy efficiency (ε) of the ohmic heating process was defined as:

$$\varepsilon(t) = \frac{SHE(t)}{SEE(t)} \qquad [2.12]$$

They found that the overall energy efficiency of a batch type ohmic heating process for coagulating fish proteins in frozen fish mince wash water was above 86 %. At low temperatures, all the electrical energy was converted to heat. As the temperature rose, the efficiency began to decrease linearly. Pain and Baudez (1994) reported that the total energy consumption of an industrial APV type ohmic heater used for particulate foods would consume, on average, 0.15 kWh per kg of finished product. The electrical power necessary to heat the product would be 0.1 kW for 1 kg/h of product. A comparison between the energy consumption for microwave and radio-frequency radiation (MW 2450 MHz, MW 896/915 MHz and RF 13.56 MHz) and Joule effect (50/60 Hz) industrial heating processes revealed that the electrical energy conversion is superior for ohmic heating (90-95%) than for MW 2450 MHz (60-70%), MW 896/915 MHz (80-90%), RF 13.56 MHz (50-60%) (Pain *et al.*, 1995) for liquids containing particles.

Energy control of the ohmic process

Roberts *et al.* (1998) established a method to control the extent of hot spot formation during the ohmic thawing of fish blocks in a fully automated process. The objective was also to set up a basis for scale-up in industrial use. The maximum current flow was kept constant and set by the operator. The energy was calculated from the voltage and current values, which can be used to calculate the actual energy at a specific time:

$$EE = VI(t) \qquad [2.13]$$

The accumulated electrical energy was determined as follows:

$$EE_{acc} = \int_0^t VI(t)dt \qquad [2.14]$$

The theoretical energy required to thaw the block was estimated from the sensible heat below the freezing point, the latent heat and the sensible heat above the freezing point:

$$HE_{below} = M\,C_{pb}\left(T_{bf} - T_{in}\right) \qquad [2.15]$$

$$HE_{latent} = M\lambda \qquad [2.16]$$

$$HE_{above} = M\,C_{pa}\left(T_{out} - T_{fp}\right) \qquad [2.17]$$

The total theoretical energy input is the summation of the three equations [2.15] to [2.17] for fish and water in the block:

$$HE_{total} = HE_{fish} + HE_{water} \qquad [2.18]$$

$$HE_{total} = \left(HE_{below} + HE_{latent} + HE_{above}\right)_{fish} + \left(HE_{below} + HE_{latent} + HE_{above}\right)_{water} \qquad [2.19]$$

A coefficient of performance was defined as the ratio of the accumulated electrical energy used (EE_{acc}) to the theoretical heating energy required (HE_{total}):

$$COP = \frac{EE_{acc}}{HE_{total}} x100 \qquad [2.20]$$

The end point of the process was determined when the total accumulated energy reached a predetermined value corresponding to the heat necessary to thaw that product.

These authors found that the designed ohmic system was able of thawing two shrimp blocks as predicted. The advantages were to avoid the use of water and be more energy efficient than conventional water immersion thawing technologies. A correlation was found between the thawing time and the COP; the longer the thawing time, the lower the COP.

ELECTRICAL CONDUCTIVITY

A key parameter

It is the electrical conductivity or the overall resistance of food that controls the ohmic heating rate. Therefore, the electrical conductivity is a key property in this process. But, how conductive or resistive should the food material be in order to observe a desirable rise in temperature? In highly conductive materials such as metals, a large current will flow. In insulators or highly resistive materials like wood, there will be a negligible current. It is important to note that in both these conditions, generation of heat will not be sufficient. Therefore, boundaries exist for the values of electrical conductivity in order to obtain sufficient heat generation. If food electrical conductivities fall outside this region, it would represent a potential threat to the heating process. Most pumpable foods contain water in excess of 30 % and dissolved ionic species such as salts and acids which render the food electrically conductive to benefit from ohmic heating (Halden *et al.*, 1990). Pure fats, oils, alcohols and sugars are not suitable materials for ohmic heating. These substances are electrically too resistive. Highly conductive materials (e.g. very concentrated salt solutions) which allows most of the current to pass through are also not suitable. There is a certain operating region (Figure 2.2) of electrical conductivities for a successful ohmic heating process, within a maximum and physically limited power (de Alwis and Fryer, 1992). However, there is sufficient flexibility to adjust food formulations by mixing highly conductive and resistive food ingredients so

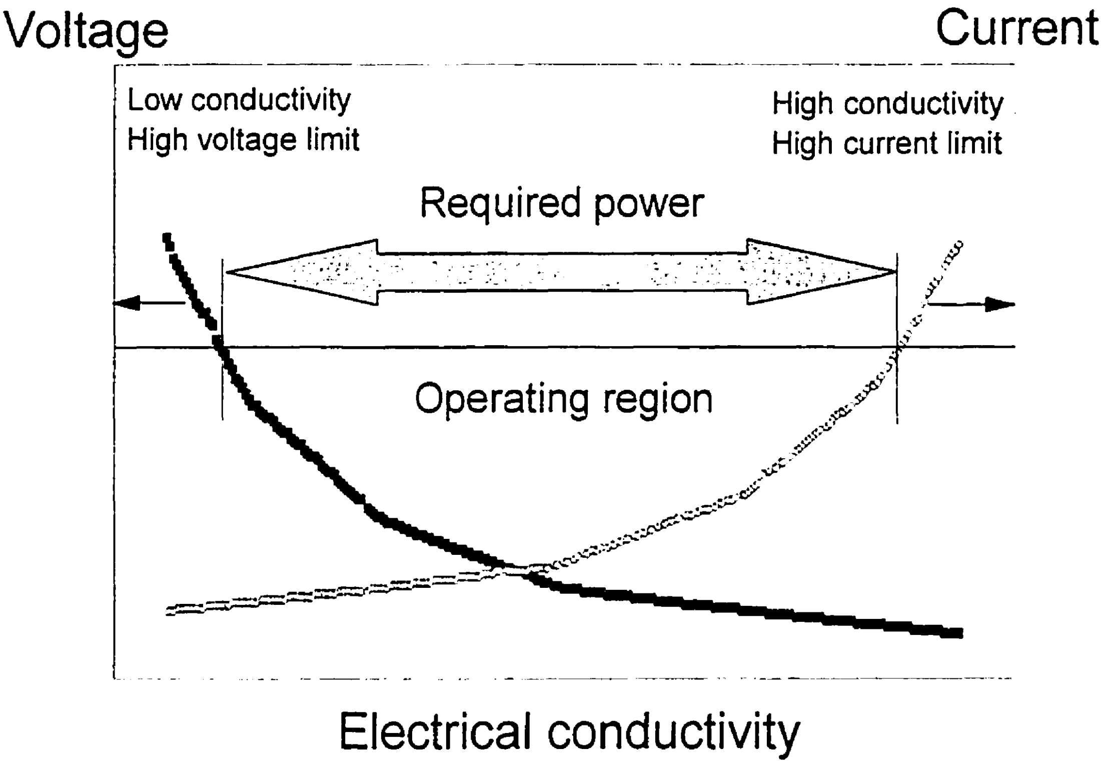


Figure 2.2 Operating region of electrical conductivity

Adapted from de Alwis and Fryer (1992) that the overall conductivity is optimal for the best efficiency of the ohmic heating process (Zoltai and Swearingen, 1996). Sastry and Palaniappan (1992c) have demonstrated that in a heterogeneous mixture, there is a higher rate of increase in electrical conductivity of a potato particle as a function of temperature than for a carrier fluid of various electrical conductivities.

Table 2.3 lists published electrical conductivity values for solid and liquid foods. Discrepancies have been reported in the literature (Palaniappan and Sastry, 1991a) with respect to the magnitude of electrical conductivity for solid foods. Therefore, it is generally difficult to compare these data. Stirling (1987) also classified electrical conductivity data for foods as a function of their heating characteristics (Table 2.3c).

Measurement of electrical conductivity

To date, research on the electrical properties of food has been to determine the mechanisms of interaction between food and electromagnetic energy mainly at microwave and radio frequencies (Mudgett, 1992). Food materials have been reported to have a wide range of electrical conductivities from 10^{-3} to about 10^{2} S/m (de Alwis *et al.*, 1989; Stirling, 1987), between conducting materials and insulators.

Devices have been developed to measure electrical conductivities of solid food pieces for various geometry's (Mizhrahi *et al.*, 1975; Mitchell and de Alwis, 1989; Palaniappan and Sastry, 1991a) as it was not easy to find commercial meters that would give results at the frequency generally encountered during ohmic heating. In its simplest form, this measurement involves the determination of the resistance of the sample between two electrodes of a fixed shape at a given distance. The ratio of L/A is usually defined as the cell constant which could vary from 1 to 50 cm^{-1} (Cummings and Torrance, 1985). Usually, the current is measured when a fixed voltage is applied. The exact geometry of the sample must be known. A ratio of the distance to diameter of four was found to give reproducible results for food materials (Mitchell and de Alwis, 1989).

Practical measurement of liquid electrical conductivity are commonly performed with commercial meters which operate at frequencies at or above 1 kHz (Mitchell and de Alwis, 1989; Halden *et al.*, 1990). The relationship between the electrical conductivity of

Table 2.3a Published electrical conductivities of various solid foods

Food Material	Electrical conductivity (S/m) at 25°C	Authors
Potato raw	0.038	Mitchell and de Alwis (1989)
	0.04	Halden *et al.* (1990)
	0.32	Palaniappan and Sastry (1991a)
	0.037	Kim *et al.* (1996a)
0.2 % NaCl	0.37	Palaniappan and Sastry (1991a)
0.4 % NaCl	0.36	Palaniappan and Sastry (1991a)
0.8 % NaCl	0.43	Palaniappan and Sastry (1991a)
Carrot raw	0.13	Palaniappan and Sastry (1991a)
	0.041	Kim *et al.* (1996a)
across axis	0.025	Mitchell and de Alwis (1989)
// to axis	0.042	Mitchell and de Alwis (1989)
0.2 % NaCl	0.29	Palaniappan and Sastry (1991a)
0.4 % NaCl	0.31	Palaniappan and Sastry (1991a)
0.8 % NaCl	0.25	Palaniappan and Sastry (1991a)
Onion	0.022	Mitchell and de Alwis
Mushrooms	0.022	Mitchell and de Alwis
Cucumber	0.027	Mitchell and de Alwis
Turnip	0.026	Mitchell and de Alwis
Parsnip	0.025	Mitchell and de Alwis
Brussels sprouts	0.009	Mitchell and de Alwis
Tomato	0.045	Mitchell and de Alwis
Leeks		
across axis	0.007	Mitchell and de Alwis
// to axis	0.032	Mitchell and de Alwis
Celery	0.026	Mitchell and de Alwis
Courgettes		
Skin on	0.017	Mitchell and de Alwis
Skinless	0.032	Mitchell and de Alwis
Pepper	0.048	Mitchell and de Alwis
Pear	0.041	Mitchell and de Alwis (1989)
Apple	0.023	Mitchell and de Alwis (1989)
Pea	0.17	Kim *et al.* (1996a)
Chicken	0.08	Mitchell and de Alwis (1989)
	0.37	Palaniappan and Sastry (1991a)
Pork	0.087	Halden *et al.* (1990)
Beef	0.44	Palaniappan and Sastry (1991b)
	0.42	Kim *et al.* (1996)
Surimi		
1% salt	1.5	Yongsawatdigul *et al.* (1995b)
2% salt	2.5	Yongsawatdigul *et al.* (1995b)
3% salt	3.5	Yongsawatdigul *et al.* (1995b)
4% salt	5.0	Yongsawatdigul *et al.* (1995b)
Canned Pet food	0.97	Mitchell and de Alwis (1989)

Table 2.3b Published electrical conductivities of various liquid foods

Food Material	Electrical conductivity (S/m)	Authors
Tomato juice	0.863	Palaniappan and Sastry (1991b)
Orange juice	0.567	Palaniappan and Sastry (1991b)
5.5 % starch solution		
0.2 % salt	0.34	Kim *et al.* (1996a)
0.55 % salt	1.3	Kim *et al.* (1996a)
2 % salt	4.3	Kim *et al.* (1996a)

Values of Kim *et al.* (1996a) were measured at 19 °C, all other values at 25 °C.

Table 2.3c Classification of electrical conductivity values (adapted from Stirling, 1987)

Product Type	Electrical conductivity (S/m) at 25°C	Heating rate (°C/s)
Pickles and chutneys	2.0-3.0	Rapid heating possible
Savoury sauces	1.6-1.8	1-5°C/s
Various soups	1.4-1.8	
Minced beef, lamb	0.8-1.2	
Pet foods	0.7-1.2	
Full-cream milk	0.52	Very rapid heating
Dairy desserts (vanilla/custard)	0.50-0.38	7-50°C/s
Beaten egg	0.4	
Vegetable pieces	0.1-0.06	
Fruit pieces	0.15-0.05	
Margarine	0.027	Unsuitable products and
Sugar syrup	0.001	conductivity too low

the liquid and the resistance across the electrodes includes a cell constant (i.e. ratio of distance between electrodes to area of electrodes). It is a common practice to maintain the resistance between limits of 10 and 100000 ohms. Most food liquids would necessitate a practical cell constant of 50 cm^{-1} (Jones, 1985). In order to measure the conductivity accurately, it is necessary to determine the cell constant. While it is possible to measure the geometry of the cell if it is large enough, the usual practice is to measure the resistance when the cell is filled with a solution whose electrical conductivity is accurately known. For reference purposes, aqueous solutions of potassium chloride are normally used. Crow (1979) reported that for high conductivities, high cell constants would be used to increase the sensitivity of the measurement (i.e. small electrodes and large distances between electrodes). For small conductivities, the ratio L/A should be very small. Therefore, large electrodes will be used and the length between electrodes will be short. Several authors (Crow, 1979; de Alwis *et al.*, 1989; Palaniappan and Sastry, 1991b; Yongsawatdigul *et al.*, 1995b) have reported that there is no voltage gradient effect on electrical conductivities of liquids.

Another important factor to control is the extent of polarisation during the measurement. This depends on several factors such as the nature of the electrode surface and the frequency of the alternating current. The restrictions arising from the electrode surface impose a choice on the material. Normally, treated or coated electrodes are used, provided that the frequency is in the range normally found in commercial instruments (50-1000 Hz). Increasing the frequency of the applied voltage can reduce polarisation. The effect of frequency is particularly important for the range of measured electrical conductivities for foods (Cummings and Torrance, 1985).

Imai *et al.* (1995) studied the effect of frequencies (50 Hz-10 kHz) on the heat generation of Japanese white radish. Of the frequencies examined, 50 Hz gave the sharpest initial rise in temperature and the shortest time to raise the temperature.

It has been shown that for fluids with a high concentration of dissolved or entrapped ions, the electrical conductivity is a strong function of the frequency (Falkenhagen, 1934). For commercial applications, the choice of frequency is usually a compromise between avoiding polarisation problems without introducing capacitive errors into the measurements (Mitchell and de Alwis, 1989; Kim *et al.*, 1996a; Fryer *et* *al.*, 1993). Since the frequency effect is important with respect to electrical conductivity values, it is necessary to measure electrical conductivities in the context of ohmic heating or at 60 Hz. There is little published information on the electrical properties of foods at low frequencies in the context of ohmic heating (Mitchell and de Alwis, 1989).

Electrical conductivity of solids

In practice, most vegetable solid particles exhibit lower electrical conductivities than liquids. Soaking treatments have been proposed, in some studies (Palaniappan and Sastry, 1991a; Wang and Sastry, 1993), to increase the electrolytic content of solid pieces of food in order to match electrical conductivities of the liquid and solid phase of particulate foods for the best efficiency of the ohmic heating process.

The effect of processing on the electrical conductivity of solid food pieces has been investigated by several authors (Halden *et al.*, 1990; Wang and Sastry, 1997a) as in most industrial operations, products will probably undergo a thermal treatment for cooking, enzyme inactivation or to raise the initial temperature prior to ohmic heating. Since electrical conductivity is a key parameter in the estimation of heating rate, it is important to study the effect of these processes. After being ohmically heated in cycles, the electrical conductivities of potato, carrot and yam increased as well as their heating rates (Wang and Sastry, 1997a). Vegetables preheated by conventional heating also showed an increase in electrical conductivity and heating rate but the thermal effect was different. The reasons are not clear but factors such as structural changes, increase in moisture and ionic mobility should be taken into account (Wang and Sastry, 1997a).

Palaniappan and Sastry (1991a) measured electrical conductivities of potato, carrot and yam samples untreated and after being soaked in water and various salt solutions (0.2, 0.4, 0.8 %) until saturated. All vegetable samples saturated with water had lower electrical conductivities than the control. Infusion of salt increased electrical conductivities, with the extent of increase dependent on salt concentration.

Imai *et al.* (1995) studied ohmic heating of Japanese white radish to examine the effect of frequency on heat generation. They found that 50 Hz was the most efficient below 50 °C. Heating rates, above 60 °C, were found to be the same and linear for all frequencies. They found that heat generation was not caused by dielectric loss but mainly by the passage of alternating current followed by electroporation of radish membrane and the resulting reduction of its impedance or resistance. The apparent critical membrane potential for the electroporation was found to be lower than that previously reported.

Electrical conductivity of liquids

Palaniappan and Sastry (1991b) reported that the effect of the percentage of solids was less important than the temperature effect, but still significant. The liquid electrical conductivity was reported to decrease with the increasing presence of solids or non-polar constituents dispersed in the liquid phase. This is to be expected since the electrical conductivity of solids is usually lower than the electrical conductivity of liquids. A typical equation was established for tomato and orange juices (Palaniappan and Sastry, 1991b) for the effect of temperature and solids content:

$$\sigma_T = \sigma_{ref} \left[1 + K_T \left(T - T_{ref}\right)\right] - K_s S \qquad [2.21]$$

Where S is the solid content. K_T and K_s are constants. The size of suspended particles was also shown to affect the electrical conductivity. Results of investigations (Palaniappan and Sastry, 1991b) on the role of particle size in carrot juice revealed that electrical conductivities increased as the particle size was mechanically decreased using a blender. It was suggested that the particle size dependence was due to a structural rather than a chemical effect.

Effect of temperature and phase

Published values of electrical conductivities are usually measured at room temperature which is not the only temperature experienced by food during ohmic heating. Early electrical conductivity measurements were investigated as a quality control tool to evaluate physiological processes during growth occurring in plant tissues (Sasson and Monselise, 1977; Bean *et al.*, 1960; Weaver and Jackson, 1966).

Wang and Sastry (1997a) reported that the effect of temperature on electrical conductivity is very important. Electrical conductivity values of raw vegetable pieces follow a sigmoid curve as a function of temperature with a slope change around 50 °C due to critical structural changes in the biological material (Figure 2.3). For liquids, formulated products and thermally treated solid vegetable pieces, it has been demonstrated, by several authors (Palaniappan and Sastry, 1991ab; Fryer *et al.*, 1993; Qihua *et al.*, 1993; Yongsawatdigul *et al.*, 1995b), that the electrical conductivity-temperature relationship is linear within a temperature range of 20 to 80°C (Figure 2.3). As temperature increased, the electrical conductivity increased. Fryer *et al.* (1993) used the following equation for viscous liquids:

$$\sigma = \sigma_0 + K_T(T) \qquad [2.22]$$

Which anchors the reference value of the electrical conductivity at 0 °C. Palaniappan and Sastry (1991b) expressed the relationship between electrical conductivity and temperature for liquids in a slightly different manner:

$$\sigma = \sigma_{25}\left(1 + K_T(T-25)\right) \qquad [2.23]$$

Roberts *et al.* (1998) reported that values of electrical conductivity of frozen fish blocks were dependent on temperature and phase. Luzuriaga *et al.* (1996) found that frozen shrimps had an electrical conductivity that was two orders of magnitude lower than thawed shrimps. They also observed a non-linear or quadratic relationship between σ and T at temperatures typically used for frozen products.

In their study on salt infusion into vegetable tissue prior to ohmic heating, Wang and Sastry (1993a) found that high salt concentration provided a strong effect on electrical conductivity when it exceeded 0.01 g/cm^3 (1 %) in potato tissue, with the σ-T relationship becoming non-linear (quadratic).

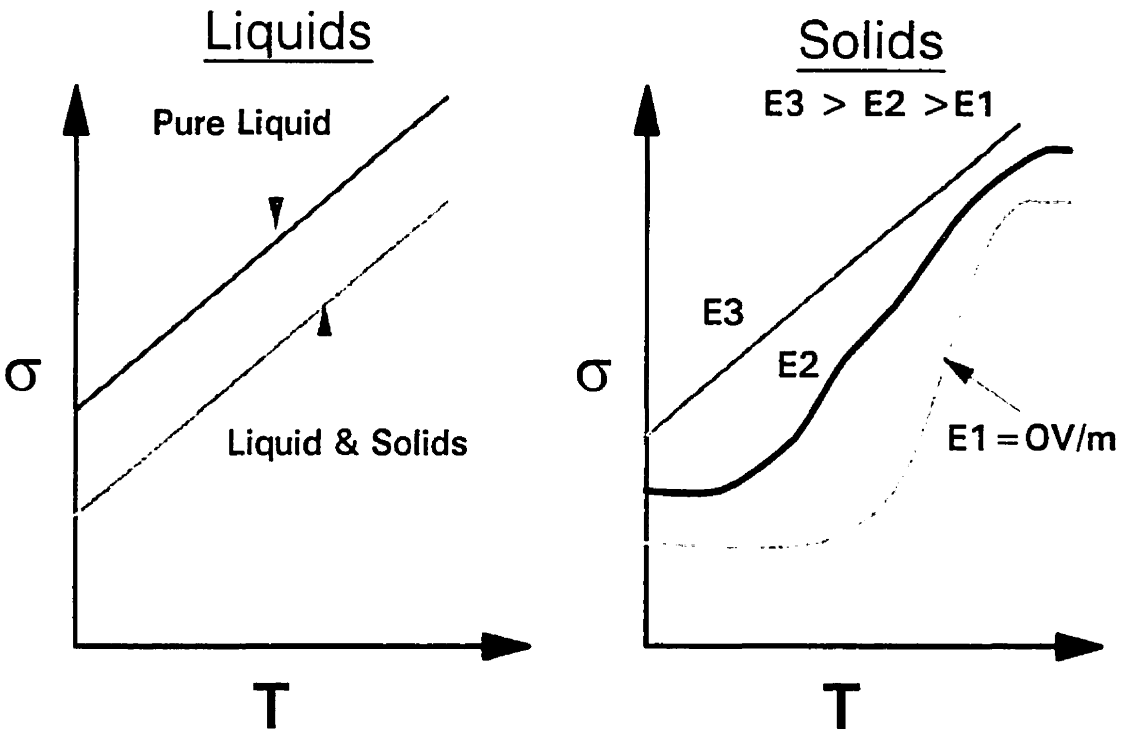


Figure 2.3 Electrical conductivities of solid and liquid foods

Adapted from Sastry and Palaniappan (1992a)

Effect of voltage gradient

The effect of voltage gradient on electrical conductivity has been reported for various solid foods (Halden *et al.* 1990; Palaniappan and Sastry, 1991a) as shown in Figure 2.3. As the voltage gradient decreases, the electrical conductivity profile as a function of temperature becomes sigmoidal with a sharp transition around 60 °C. Sigmoidal curves are also obtained during conventional heating conditions which would represent a field gradient of about 0 V/cm. For a sufficient voltage gradient, the electrical conductivity of solids varies linearly with temperature. Palaniappan and Sastry (1991a) reported that electrical conductivities of solid food pieces decreased with decreasing voltage gradient especially at 20 °C. Values reported by Mitchell and de Alwis (1989) for solid food pieces appear to have been gathered at 20°C with a very low voltage gradient. Palaniappan and Sastry (1991a) tried to explain the reasons for the changing shape of the curve with increasing applied voltage. This phenomenon was attributed to electro-osmotic dehydration with a consequent tissue softening (Halden *et al.*, 1990; Palaniappan and Sastry, 1991a) high-applied electric field enhanced cell fluids motion within plant cells and ruptured cell membranes.

According to Crow (1979), when applying a few volts to electrolytic solutions, there is no measurable variation in electrical conductivity with the voltage gradient. At 100 kV/cm, some differences may be observed. Palaniappan and Sastry (1991b) reported no effect of voltage gradient (30-60 V/cm) on the electrical conductivity of orange juice, a low viscosity fluid. Yongsawatdigul *et al.* (1995b) found that a high salt concentration (3-4 %) in surimi must exist to observe an effect of voltage gradient on electrical conductivity. They attributed this phenomenon to corrosion of the electrodes since it is unlikely that motion of cell fluids would be enhanced in homogeneous liquids.

Overall electrical conductivity

When homogeneous foods such as liquids and solids are ohmically processed, the establishment of an ohmic heating process is simplified. However, in the case of heterogeneous foods such as a mixture of liquid and solid particles, the overall conductivity of the system controls the basic operating conditions. Ideally, the electrical conductivities of solid particles and carrier liquid should be closely matched for the heating rate to be similar but this is not always possible. Generally, it is found that ohmic heating is more efficient if a high ratio of solid particles to liquid is used. Finally, orientation or irregular shaped particles in the field was observed to strongly influence the heating rate of the particle in the liquid. Palaniappan and Sastry (1991c) pointed out the importance of knowing the effective conductivity of two-phase continuous flow systems. However, measurement of electrical conductivity of two phase continuous flow systems under all possible conditions is complicated.

EFFECT OF ELECTRICITY ON FOODS

Ohmic heating is usually considered as a thermal process i.e. an electrical current is used for heat generation through an electrically resistant food system. However, electrical treatment of foods can be applied in a variety of ways (Palaniappan and Sastry, 1990) which may result in additional electrical or non-thermal effects on food systems. Either continuous (DC) or alternating current (AC) may be used. Electrical treatment may be delivered either continuously or by rapid discharges (pulses) with or without any heat generation. The range of voltages for ohmic heating is between 3 kV and 12 kV while the range for high voltage impulses is between 14 kV and 35 kV. Low frequency technologies have been investigated as possible "cold" pasteurisation processes. Pulsed electric fields (Jayaram and Castle, 1992; Castro *et al.*, 1993) and oscillating magnetic fields (Pothakamury *et al.*, 1993) are included (Barbosa-Canovas *et al.*, 1998).

Ionic losses and penetration depths become quite large at low frequencies (kHz region) under ohmic heating conditions. Ohmic heating involves the dissipation of electrical energy by conduction into the food product as a dielectric material in contrast to radiative energy transfer at high frequencies. One consideration is that polarisation effects occur that result in the outgassing of electrolytic products and fouling or electroplating of the electrode surface unless the electrodes are platinized or coated with an inert material that prevents direct contact.

Effect on micro-organisms and enzymes

A number of studies have been performed to measure the effect of electricity on micro-organisms and enzymes in cell suspensions or in food directly under a variety of conditions (Palaniappan and Sastry, 1990; Palaniappan *et al.*, 1992; Imai *et al.*, 1995). Three effects, by which electricity causes microbial death, have been identified 1) mechanical 2) chemical 3) thermal (Palaniappan and Sastry, 1990; Bhat and Joshi, 1998).

So far, microbial inactivation during continuous low-voltage alternating electrical treatments has been attributed primarily to heating (Palaniappan and Sastry, 1990). In the early 1920's, the Electro-pure process (Andersen and Finkelstein, 1919) was examined by several US state health departments before being approved and commercialised. It was concluded that there was no additional electrical effect on milk. Milk was stabilised solely by a thermal effect. As well, with low voltage alternating current, enzymes are inhibited due to the heat generation (Mizhrahi *et al.*, 1975). Palaniappan *et al.* (1992) compared ohmic to conventional heating on suspensions of yeast (*S. Bailii*) and bacteria (*E. coli*). They concluded that microbial death was primarily due to thermal effects with no significant effect coming from electrical current.

Studies using high-voltage pulses in aqueous suspensions of micro-organisms reported a lethal effect on the microbes caused by the electrical current (Mertens and Knorr, 1992; Barbosa-Canovas *et al.*, 1998). Under high voltage impulses, it is believed that mechanical damage occurs. Pores are created in cell membranes of bacteria causing their death. One of the proposed mechanisms for pulsed electric field is the "dielectric rupture" theory that postulates that a critical transmembrane potential of about 1V is obtained at some critical field strength (e.g. 13-16 V/cm for vegetative strains of *Lactobacillus* and *Escherichia* and higher field strengths for spore-forming bacteria and fungi).

In electro-hydraulic shock experiments, a rapid electrical discharge is applied to a suspension of micro-organisms without any heat generation. Under these conditions, the reduction in the number of micro-organisms was attributed to oxidation reactions (e.g. formation of hydroxyl, hydroperoxides, free radicals with oxygen, toxic metal ions from the electrodes and toxic chlorinated compounds).

Cho *et al.* (1996) compared a conventional and an ohmic fermentation of *Lactobacillus acidophilus* at three temperatures (30, 35 and 40 °C). Using ohmic heating, a constant temperature was maintained by intermittently circulating cooling water through the water circulation coil. The electric current was found to enhance early stages but to slightly inhibit the late stages of growth. The production of bacteriocin was reduced during ohmic heating. It was also mentioned that it was possible to monitor the progress of the fermentation by monitoring the current at a constant voltage.

Papers on ohmic heating of potato (Schade, 1951) and corn (Mizhrahi *et al.*, 1975) have demonstrated its applicability as a blanching treatment. Enzymes responsible for discoloration were inhibited by heating.

Effect on solid foods

Solid foods such as plant tissue are composed of individual cells isolated by the cell membrane and wall. The major constituents of the cell membrane are phospholipids and can be regarded as an electrical condenser. When the applied voltage increases and induces a membrane potential greater than 1 V, pinholes are created because of a potential discharge. This occurs within a very short time (micro-seconds). This phenomenon, electroporation, is well documented in the genetic transformation of cells (Tsong, 1990), inactivation of micro-organisms (Hulsheger *et al.*, 1983) and equipment design for extending the shelf life of liquid foods (Dunn and Perlman, 1987; Bushnell *et al.*, 1991). The surrounding water will enter the cell due to osmotic pressure and the cell will expand and rupture. Electroporation has mainly been observed under direct current.

Nevertheless, Uemura and Noguchi (1995) reported that with AC at high frequency (10 kHz), the duration of electrode polarity is sufficient to cause induced membrane potential and subsequent electroporation.

Ohmic heating was examined in Japanese white radish at various frequencies (Imai *et al.*, 1995). In their study, they found that the initial rapid heating (until 50 °C) at low frequency (50 Hz) was caused by electroporation of the radish tissue membrane. They measured the impedance after ohmic heating at 50 Hz with a 40 V/cm field gradient for 10, 30 and 50 s with negligible heat effects. The impedance was reduced considerably. Halden *et al.* (1990) reported a similar result for beetroot after ohmic heating at 50 Hz.

The presence of an electric field has been found to produce additional effects such as mass transfer in foods. Moisture changes in potato slices were enhanced during electro-blanching (Wigerstrom, 1976). Electro-osmosis occurs in an AC field due to molecular diffusion.

The dissolution of protopectin and other cell wall constituents such as hemicellulose, can result in the loss of cell rigidity and intercellular adhesion and will affect food electrical conductivities. This will increase stress on membranes and may lead to cell lysis. The breakdown of cellular arrangement can lead to higher conductivity due to increased ionic mobility. Electrical conductivity changes have been reported due to starch gelatinization in potato (Halden *et al.*, 1990). The rate of plasmolysis of sugar beet tissue is usually increased by the presence of an electric field and is used to increase the efficiency of sucrose extraction from sugar beet (Fedorchenko *et al.*, 1983).

Athayde and Ivory (1985) reported that an AC field can increase the rate of ion transport between solution and cells affecting carrier mediated transport across cell membranes overcoming the diffusion limitation. As well, an AC field can lead to an increase in diffusion across liquid membranes due to electrohydrodynamic mixing.

Effect on liquid foods

The nature of ions (chemical composition), ionic movement and the viscosity of the liquid affect the electrical properties of liquids. All of these are temperature dependent (Palaniappan and Sastry, 1991b).

Effect on biopolymers

Under a DC current, movement of charged species can occur in biopolymers. This is a type of electrophoresis wherein the water is moved to the cathode while biopolymers such as proteins are moved to the anode.

Park *et al.* (1995) performed a study on the effect of ohmic heating on fish protein gel. The structure of the gel was examined using scanning electron microscopy. As well, the breaking strength and colour were measured using conventional methods. Electrical properties were recorded. The electrode corrosion was examined by immersion in NaCl. It was found that over 100 Hz, gels had similar electrical properties, which would tend to prove that heating rates would be similar. However, specific heating rates increased remarkably as the frequency increased from 1 kHz to 10 kHz. This indicates that there was a significant dielectric loss in the gel. Corrosion of aluminium electrodes increased at 50 Hz with increasing NaCl concentration. There was a negligible contamination of aluminium ions in the product as the frequency was increased to 50 kHz.

Wang and Sastry (1997b) studied the effect of starch gelatinization on electrical conductivity. Suspensions of corn and potato starch were prepared in water (1:5 w/w) and were ohmically treated to 90 °C using a voltage gradient of 20 V/cm. Ungelatinized, partially gelatinized and fully gelatinized suspensions were tested. Endothermic gelatinization peaks were found for both DSC thermograms and electrical conductivity curves as a function of temperature. The percentage of starch gelatinization as determined by DSC thermograms and σ-T curves correlated well in the in low and mid-gelatinization ranges. Different results were found under a high percentage of gelatization probably due to the high ohmic heating rate. Therefore, the potential for quantifying starch gelatinization by electrical conductivity changes vs. temperature has been demonstrated. An on-line ohmic heating sensor could possibly be installed to monitor starch gelatinization in a food processing unit operation. Furthermore, it was found that electrical conductivity increases with temperature but decreases with the degree of gelatinization, apparently caused by structural changes and an increase in bound water.

MODELLING OF OHMIC HEATING

Modelling of electrical conductivity

Several models have been used to predict the electrical conductivity of food systems. Physicochemical models predicting the electrical properties of foods as functions of frequency, temperature and chemical composition have been reported mainly for microwave and radio-frequency conditions (Mudgett, 1992). In the literature, these have been developed based on either the classical Maxwell theory or on the electrical circuit model. Maxwell (1954) developed the model to determine the effective conductivity of a dilute dispersion of spherical particles. Meredith and Tobias (1961) modified Maxwell's model to account for interaction of fields around particles in emulsion. Simple series and parallel models were used to predict electrical and thermal conductivities of two component systems (Murakami and Okos, 1989). Kopelman (1966) presented anisotropic models, which may be more applicable to real food systems. Palaniappan and Sastry (1991c) developed a probability model. Results from these models indicate that predictions are in reasonable agreement with experimental data (Sastry, 1992c).

Modelling of the ohmic heating process

Like conventional aseptic processing of particulate low-acid foods, the temperature of the liquid and the particle must be known to assess the efficiency of the ohmic heating process. For moving particles, it is difficult to monitor the temperature without interfering in the process; therefore we must rely on modelling to predict the temperature. A full model in ohmic heating requires the simultaneous solution of the electrical, flow and thermal differential equation in the geometry of the ohmic heater. For static thermal design, it is not necessary to model the flow explicitly, only the coupled electrical and thermal partial differential equations (PDE) are solved to find the temperature distribution.

Models have been developed for ohmic heating of solid-liquid mixtures that have been validated experimentally for a single particle in a static heater (de Alwis and Fryer, 1990c; de Alwis and Fryer, 1990b; Fryer *et al.*, 1993). For multiple particle systems in either static or continuous flow ohmic heaters, simplified models have been presented (Sastry and Palaniappan, 1992c; Sastry, 1992abc; Sastry and Li, 1993; Zhang *et al.*, 1992; Zhang and Fryer, 1995; Sastry and Salengke, 1998; Orangi and Sastry, 1998) for a limited number of particles. Table 2.4 summarises the various published models, conditions and major findings.

Two different approaches have been used for the calculation of the electric field within the system. De Alwis and Fryer (1990b) demonstrated that the electric field within a system, in which the electrical conductivity varies with position, could be modelled by solving Laplace's equation with appropriate boundary conditions. At the electrodes, a uniform voltage is assumed (i.e. Dirichlet conditions). Elsewhere, there is no current flow across the boundary as for homogeneous Neumann conditions. The resulting equation is:

$$\nabla \cdot (\sigma \nabla V) = 0 \qquad [2.24]$$

This is the steady state form of the current continuity equation that governs the electrical field. Zhang *et al.* (1992) extended the approach and suggested a model which assumed that sections of the fluid or repeating "unit cells" could be modelled as representative of the whole system.

A circuit analogy approach was used by Sastry and Palaniappan (1992c) for the solution of the electric field in a static and a continuous ohmic heater where particles and liquid are present. A set of equivalent resistances for the liquid and particles were computed for each incremental section consisting of two resistances in parallel for the liquid and the particles and one resistance in series for the liquid. These resistances were calculated from the length and the area of the cross section of the incremental section and electrical conductivities of the liquid and particles. This approximation was found to be realistic, more applicable to multiparticle mixtures and to be more expeditious. It is difficult to model a liquid containing particulates without an attempt to represent a volume element of the two-phase mixture in movement.

Table 2.4 Review of mathematical models, their conditions and major findings

Authors	Conditions	Majors Findings
de Alwis and Fryer (1988)	. Static heater 240V, 50 Hz . One particle . 2D finite element . Laplacian . electric field distribution . Runge Kutta 4th order . temperature vs. time . No convection/fluid flow	.Heating rate depends on particle size and geometry . Solid phase heats faster or at a comparable rate as liquid phase
de Alwis *et al.* (1989)	. Static heater 240 V, 50 Hz . One particle . T from 20 to 90°C . Potato pieces 0.06 S/m in liquid of 0.58 S/m . Egg albumin pieces 2S/m in liquid of 0.38 S/m . Thin shape parallel and perpendicular to the field . Analytical solutions of the simplified Laplace equation	. Potato heated faster than the liquid when perpendicular to the field and slower when parallel . Egg albumin heated faster than the liquid when parallel to the field and slower when perpendicular . High aspect ratio / thin enough that conduction ensures that its heating rate is not affected by orientation
de Alwis and Fryer (1990b)	. 2D finite element . One particle, static heater . Laplace equation . electric field distribution . Zero convection . Enhanced conduction . Well stirred liquid . Validation with an analytical solution	. Heating rate is highly susceptible to the orientation of the particle to the field . Particle heating rate is a function of electrical conductivity of both phases together with particle size, shape and orientation to the electric field
de Alwis and Fryer (1990c)	. Alternative method for modelling heat generation in the solution of coupled electric and thermal fields . Equivalent network of resistances	. Saving computer time
de Alwis and Fryer (1992)	. Static heater . 2D finite element . Laplace equation . Heat generation and conduction . One particle // and perpendicular to the field . Examination of various electrical conductivity values	. High aspect ratio particles are problematic (i.e. long and thin) . Particle parallel to the field heats faster if less conductive than liquid . Particle perpendicular to the field heats faster if more conductive that liquid . Electrical conductivity variation of ± 5% in each phase is acceptable

Fryer *et al.* (1993)	. CMC and salt solutions . Liquid temperatures . Batch ohmic heater . Analytical solution . No conduction . infinite thermal conductivity . natural convection . One particle	. High viscosity (HV) solutions heat more quickly than the water . Due to a lack of convention . Higher temperatures in the region of maximum current density . For low viscosity (LV) solution, temperature differences negligible . Good agreement between experiments and simulations using infinite thermal conductivity case except at high temperatures . Well stirred liquid for LV
Zhang and Fryer (1993)	. Static heater . One particle . Food mixture as homogeneous . Section can be modelled as representative of the whole . « unit cells » . higher solids fraction	. Model developed for multiple particles in liquids
Zhang and Fryer (1995)	. Comparison of alternative formulations for the prediction of heating rate	. Circuit analogy approach is not appropriate for mixtures containing low solids fraction < 30% solids . Laplace equation is computer time consuming to solve for the electric field distribution
Sastry and Palaniappan (1992b)	. Mathematical determination of the orientation to the field and its effect on heating rate of particle for a cubic particle . One particle	. Slight effect of orientation on the resistance of the mixture . Effect is more important as the difference in electrical conductivity is important but still less than 10% . If particle shapes are carefully controlled, orientation effects are minimised
Sastry and Palaniappan (1992c)	. 3D finite element model . Static heater . Well stirred liquid . Low viscosity liquid . Equivalent electrical analogy . Validation with two particles and multiple particles . Experimental verification : potato cubes and sodium phosphate solutions	. Use of high solids concentration is conducive to rapid particle heating . Critical parameters were electrical conductivities of the two phases and volume fraction

Sastry (1992a) and Sastry and Li (1993)	. Continuous heater . Cylindrical co-ordinates . Well stirred liquid . Plug flow assumption . 3D finite element in space . Crank-Nicolson finite difference in time . Circuit analogy for the calculation of the electric field distribution . Newtonian liquid and no viscosity effect considered	. Particle cold-spot temperatures were found to consistently exceed that of the fluid . Cold spots located at the corners . All low conductivity particles relative to the fluid, they will heat faster than the liquid but heating of the mixture is slower . An isolated low conductivity particle will exhibit large thermal lags relative . Fast moving particles will tend to thermally lag the fluid but the extent is less that in conventional thermal processing . Minor role of the surface heat transfer coefficient between the particle and the fluid
Sastry and Salengke (1998)	. Comparison of Circuit Analogy Mixed Fluid (CAMF) and Laplace Equation No Convection (LENC)	. More conservative prediction of temperature of a low electrical conductivity inclusion particle than the LENC approach . LENC is more conservative the inclusion of higher electrical conductivity than the fluid . Worst case scenario is not necessarily with a stationary fluid
Orangi and Sastry (1998)	. Continuous ohmic heater . Cylindrical co-ordinates . Solid-liquid mixtures . 3D model . Non Newtonian liquid . Fully developed flow at steady state and variation with the radial position	. Thermal inversion point occurs . Heating rate of liquid is higher at the beginning and after time heating of solids exceeds that of liquid . if $\sigma_s = \sigma_l$, $T_s - T_l$ = small . if $\sigma_l = \sigma_s$, $T_s - T_l$ = large . then low h_{fp}, mixture heats more rapidly and high h_{fp}, mixture heats slowly . Particle size has a small effect
Zaror *et al.* (1993)	. Continuous heater . Single particle in a liquid . Plug flow is assumed . Both phases at the same velocity . No temperature gradient in the radial direction . Rate of heat generation is independent of position . Liquid surrounding a single	. Minimum residence time in the heater affected by the intensity of the heat source in the liquid, the liquid density and specific heat . For low solid conductivity, the hold time is very sensitive to the solid density, specific heat capacity, thermal conductivity and particle size

	particle assumed to be perfectly mixed . No heat losses to surroundings . Thermophysical properties constant . Microbial death kinetics considered . Ohmic heater and hold tube	. If solids heat generation higher than liquid, sterilisation completed at the heater outlet. T_s rise faster than T_l . Small Biot, rate of heat generation of solid < liquid, interphase heat transfer is important . Laminar flow leads to similar problems to those encountered in conventional heating
Muller *et al.* (1994)	. Continuous ohmic heater . Liquid foods only . Cylindrical co-ordinates . Laplace equation . Same electrical conductivity . Effect of temperature on viscosity and electrical conductivity . Cooling of the wall considered . Use of dimensionless number . Newtonian (glycerol and water) . Non Newtonian fluids (CMC medium and high viscosity . Food Fluids (tomato juice and malt extracts)	. Velocity profiles determined by the difference in viscosity between wall and the centre of the heater . Non Newtonian behaviour becomes only important when the flow behaviour index is less than 0.6 . For a fixed design, performance increases with the product activation energy . Wall cooling is a necessary part of the ohmic heater . Uniformity of temperature achieved by smaller heater radius and longer tube lengths or lower liquid throughput
Quarini (1995)	. Thermohydraulic aspects of ohmic heating . No experimental verification . Vertical pipe considered . Thermophysical properties are independent of temperature . Radial and azimuthal flow velocity is 0 . No heat losses to the surroundings . Steady state condition . Bulk vertical temperature gradient is constant . Plug flow is assumed	. Flat velocity distribution at the centre of the pipe rising rapidly at the walls . Hottest temperatures found in regions of lowest velocity (near the wall) . If buoyancy becomes important, flow reversals can occur and this could lead to RT problems . To enhance uniformity : cooling of walls, engineering desired conductive-temperature characteristics

A comparison of these two approaches for the prediction of electrical heating rates (Zhang and Fryer, 1995) has shown that for the low solids fraction, the use of circuit analogies for the prediction of heating rates was not appropriate. De Alwis and Fryer (1990c) suggested a possible alternative to model the heat generation. The numerical method used a resistance network analogy to save computing time.

Sastry and Salengke (1998) also compared the two approaches in detail: one involving the solution to Laplace's equation without convective effects, as suggested by de Alwis and Fryer (1990b) and extended to Zhang *et al.* (1992) to include multiple spheres uniformly distributed within a stationary medium. The other approach, involving the use of circuit theory and a well-mixed fluid assumption, was used for a static and continuous flow ohmic heating system of high solids concentration. They obtained identical results when solid and fluid electrical conductivities were equal. When the solid was of lower electrical conductivity than that of the fluid, the Circuit Analogy Mixed Fluid approach (CAMF) was more conservative. In that situation, the worst-case scenario was not necessarily associated with a stationary fluid situation. Under the less likely condition where the solid was more conductive than the fluid, the Laplace Equation No Convection (LENC) was more conservative.

General energy transfer

Since temperature prediction is the primary target, the thermal energy transfer balance needs to be solved. The general energy problem for the liquid is expressed as follows:

$$\rho_f C_{pf} \frac{DT}{Dt} = \nabla \cdot \left(k_f \nabla T \right) + q^{\cdot} - p \nabla \cdot v - \nabla \cdot q_r + \Psi - q_p \qquad [2.25]$$

The derivative on the left-hand side is the substantial derivative defined as:

$$\frac{DT}{Dt} = \frac{\partial T}{\partial t} + v \cdot \nabla T \qquad [2.26]$$

The first term ($\nabla \cdot (k_f \nabla T)$) of equation [2.25] on the right-hand side represents the heat transferred by conduction through the fluid, the second term (q'') is the energy generation rate, negligible in conventional thermal processing but very important in ohmic and microwave heating. The third term ($p \nabla \cdot v$) represents the work done by the fluid on its surroundings, usually zero in the case of an incompressible fluid. The fourth term (∇q_r) is the radiative heat transfer, negligible for food fluids under these conditions. The fifth term (ψ) is the viscous dissipation, significant in scraped surface heat exchangers but negligible in holding tube or ohmic heaters. The sixth term (q_p) is the energy transferred to the particles in suspension. In the case where only the liquid is ohmically processed this term would be zero. The energy transfer to the particles is given by:

$$q_p = \sum_i \left(h_{fpi} A_i / V_i\right)\left(T_{bf} - T_{spi}\right) \qquad [2.27]$$

For each i^{th} particle, the value of the surface temperature, area and convective heat transfer coefficient would be different and it should be determined by the solution of the conduction heat transfer equation with an energy generation term:

$$\nabla \cdot \left(k_{pi} \nabla T_{pi}\right) = \rho_{pi} C_{ppi} \frac{\partial T}{\partial t} + q_p \qquad [2.28]$$

The conduction heat transfer equation for each particle is subject to the following surface condition:

$$k_{pi} \nabla T_{pi} \cdot \vec{n} = h_{fpi} \left(T_{spi} - T_{bf}\right) \qquad [2.29]$$

Finally, the wall boundary condition is expressed:

$$U_w \left(T_{bf} - T_{sw}\right) = k_f \nabla T_f \cdot \vec{n} \qquad [2.30]$$

U_w is an overall value, incorporating convective and wall conductive resistances and can be assumed to be 0 if the walls are insulated. The boundary condition at the inlet is:

$$T|_{z=0} = T_i \qquad [2.31]$$

The initial condition usually assumes the same temperature everywhere i.e. $T_p = T_f = T_i$ at t=0 and that it is uniform. To solve this equation, the velocity fields are necessary and can only be found from the simultaneous solution of the momentum transfer problem. As well, rheological properties of food fluids as a function of temperature should be available. In case that a mixture of liquid and solids is processed, the process of solving these equations is even more complex because the surface particle temperature must be known, this requires the solution of the conduction heat transfer equation for each particle. The fluid-to-particle interfacial heat transfer coefficient should also be used. Relevant assumptions in solving the PDE are often made such as constant thermal properties, homogeneous and isotropic particle, pure conduction heating within the particle and no phase change in the fluid and particle during processing.

General momentum transfer

The momentum transfer is mainly used to predict velocity field or the residence time distribution which can be handled also by experimental techniques. The general equations for fluid flow (Navier Stokes equations) can be found in standard textbooks (Bird *et al.*, 1960). Three systems of co-ordinates can be used i.e Cartesian (xyz), cylindrical (rθz) or spherical (rθφ). For one system of co-ordinates, three equations are established, which renders the system complicated. When considering a vertical cylindrical column in which electrodes are inserted, it is proper to use cylindrical co-ordinates. In these systems, an axi-symmetric problem is usually assumed, meaning that all field quantities are independent of θ and v_θ is essentially 0 (i.e. there is no swirling motion) which leads to only one important equation in the z-direction only:

$$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+v_z\frac{\partial v_z}{\partial z}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\,\eta_a\frac{\partial v_z}{\partial r}\right)-\frac{\partial p}{\partial z}+\frac{\partial}{\partial z}\left(\eta_a\frac{\partial v_z}{\partial z}\right)+g_z(\rho-\rho_o)\text{[2.32]}$$

Further simplifications can be made for the velocity in the r-direction, v_r. It can be assumed to be very small or zero when compared to axial velocities. In continuous systems, only steady state conditions are of interest. The variation of the axial velocity with time is 0. There is a natural convection term arising from the temperature difference between the wall and the centre of the tube resulting from changes in density. Using the Boussinesq approximation (Incropera and Dewitt, 1990), it is possible to express changes in density by changes in temperature, considering a coefficient of expansion. The resulting simplified equation can be obtained:

$$\rho\, v_z\frac{\partial v_z}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\,\eta_a\frac{\partial v_z}{\partial r}\right)-\frac{\partial p}{\partial z}++\beta\, g_z(T-T_o) \qquad \text{[2.33]}$$

Liquid temperature

Ohmic heating of the liquid phase was not studied as much as that of solids (Fryer *et al.*, 1993). The general energy balance for ohmic heating of liquids is expressed by the following equation in cylindrical co-ordinates for a continuous system:

$$\rho C_p\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+v_z\frac{\partial T}{\partial z}\right) = \dot{Q}+\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \qquad \text{[2.34]}$$

Conduction in the axial direction can be neglected because this term will be small as compared to axial convection. At steady state, the following equation is obtained:

$$\rho C_p\, v_z\frac{\partial T}{\partial z} = \dot{Q}+\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) \qquad \text{[2.35]}$$

For the special case of negligible radial velocity variations and radially well-mixed fluid i.e. a plug flow situation (Sastry, 1992a; Sastry and Palaniappan, 1992c; Sastry and Li, 1993; Sastry and Li, 1996), the fluid heat transfer problem is reduced to a one-dimensional computation. For a continuous ohmic heater:

$$m_f C_{pf}\left(T_f^{n+1} - T_f^n\right) = Q_f V_f + n_p h_{fp} A_p (T_{sm} - T_{fm}) + UA\left(T_a - T_{fm}\right) \quad [2.36]$$

Where T_{sm}, is the particle mean surface temperature; T_{fm}, is the particle mean liquid temperature at incremental location. V_f, is the volume of fluid in an incremental section of the fluid. This was found to be appropriate for low viscosity liquids (Sastry and Palaniappan, 1992c)

To understand the thermal behaviour of the liquid phase in a static heater, Fryer *et al.* (1993) used two simple limiting cases of an infinite linear field around a two-dimensional electrically insulated cylinder (wooden cylinder of 38 mm diameter): 1) no heat conduction and a constant electrical conductivity of the liquid 2) infinite thermal conductivity i.e. conduction and convective heat transfer is infinitely fast. Available analytical solutions for both simplified cases were used to model liquid temperature in a static ohmic heater. A salt solution was used for low viscosity liquid whereas a CMC solution represented a high viscosity solution. Only the initial rate of change of liquid temperature with time was well predicted as compared to experiments using the first limiting case of no heat conduction. Using the hypothesis of an infinite thermal conductivity, theory and experiment were comparable for low viscosity solutions. Therefore, the bulk fluid is well mixed for low viscosity solutions in a static ohmic heater. At high temperature, the model overpredicted the liquid temperature. With the exception of a thin particle with the long face parallel to the electrodes, no significant differences in solid heating rate occurred whether in low or high viscosity liquids. A more complex model is needed for intermediate cases where the rate of heat transfer is neither zero nor infinity or for other geometry. Free convection was included in some models but no study was performed on forced convection.

Particle temperature

Most published models have attempted to describe the thermal behaviour of particles. In this case, the conduction heat transfer equation and a temperature dependent internal energy generation govern heat transfer for particles. Equations 2.28-2.31 are used to solve for the temperature profile.

Finite element method

The resulting partial differential equations (PDE) in real systems are highly non-linear because of the temperature dependence of physical properties. Numerical methods are generally used to solve the system of equations by either finite difference or finite element methods. For handling complex geometry and a variety of boundary conditions, the finite element technique is preferred. The theory to handle such situations is well-developed (Huebner and Thornton, 1982). An iterative procedure is used to establish the time-temperature profile within a particle and of the fluid during ohmic heating. Several diagrams have been published illustrating the procedure (de Alwis and Fryer, 1990c; Sastry and Palaniappan, 1992c; Muller *et al.*, 1994; Quarini, 1995; Uemura *et al.*, 1996a). First, the electric field distribution is determined. Then, the heat generation is calculated and the energy balance equation solved to obtain the temperature profile. Finally, thermophysical properties are adjusted for the next time step. For ohmic heating, the 2-D model for the evaluation of the field distribution was solved using the method of weighted residuals with triangular elements (de Alwis and Fryer, 1990b). A fourth order Runge-Kutta integration was employed to solve the resulting set of ordinary differential equations (ODE) from the finite element modelling of the transient heat generation and conduction within particles. A three-dimensional model has also been developed (Zhang *et al.*, 1992; Sastry, 1992a; Sastry and Palaniappan, 1992c). A 3-D finite element in space and a Crank-Nicolson finite differencing in time was used to solve the model for static and continuous heaters. A weak variational formulation was implemented. Uemura *et al.* (1996a) have used quadrilateral elements with 4 nodes in each and a Crank Nicholson procedure for the time step evaluation to solve for the temperature profile in a static heater. Recently, Davies *et al.* (1999) have modelled the electric field and temperature distribution of a liquid containing one particle in a static heater in two dimensions using the finite element method. A commercial computational fluid dynamics software package was used (FIDAP) to solve the energy and potential field equations. Only thermal conduction and heat generation were considered for the particle and the liquid. It was found that the presence of a single inclusion of significantly different electrical conductivity would have an effect on the temperature distribution. A cold shadow was observed upon the inclusion of an electrical insulator solid piece in the thermal field. Inclusion of an electrically conductive particle could create portions that could overheat or underheat with respect to the surrounding liquid.

Although these equations can be solved numerically, their accuracy is strongly dependent on information from a number of parameters that are interrelated: 1) electrical conductivities of particles and carrier fluids; 2) RTD of particles; 3) thermal properties of particles and 4) rheological properties of fluids.

Sensitivity analysis of modelling parameters

Early results indicated that physical factors which affect the ohmic heating rate were particle shape, liquid and solid electrical conductivities and orientation between the solid and the electric field (de Alwis *et al.*, 1989). A range of conductivities, resulting in uniform heating, have been examined by finite element simulation (de Alwis and Fryer, 1992). A conductivity variation of ± 5 % in each phase was found to be acceptable. Sastry and Palaniappan (1992b) demonstrated that for cubic particles, orientation effects were small; the orientation effect increased as the solid-to-liquid electrical conductivity ratio increased but these results were not applicable to cases involving long thin particles and for situations involving large particle populations.

Experiments with high viscosity solutions of the same electrical conductivity have shown enhanced heating rates, due to the higher temperature coefficients of the electrical conductivity of viscous solutions (de Alwis *et al.*, 1989). Significant differences in solid heating rate were reported in high viscosity solutions (Fryer *et al.*, 1993).

Zaror *et al.* (1993) developed a simple model to evaluate key variables on the performance of a continuous ohmic heating process and to compare it with conventional thermal sterilisation in a continuous steam heater. The governing equations describing the operation of an ohmic heater were formulated on the basis of simple unsteady-state energy balances in both solid and liquid phases. The minimum residence time in the ohmic heater was found to be sensitive to the electrical field gradient intensity in the liquid, the liquid density and the specific heat. Four key physical parameters: rates of heat generation in the two phases, the Biot number and the death kinetics were reported to play a major role in the predicted performance of the system. When the heat generation rate was higher in the solid than in the liquid phase, sterilisation was found to be complete at the heater and overheating of the particle occurred. For a lower solid heat generation rate as compared to the liquid, the heat transfer for small Biot number limited the process. The process was controlled by the rate of heat generation and the microbiological kinetics. For laminar flow, overheating near the walls and significant temperature gradients were observed.

Dimensional analysis

Dimensional analysis is the simplest practical method of reducing the equations that describe a process into a form containing no reference to units of measurements for scale-up or scale-down considerations. The dimensional analysis of the problem gives a relationship between the independent and dependent variables grouped together to form dimensionless entities so the advantages of a dimensional analysis are: 1) a relationship is obtained between the process independent and dependent variables that is independent of process scale; 2) it simplifies the view of the problem, making data analysis more straightforward; and 3) it may be used to gain insight into the nature of the scale-up problem (Valentas *et al.*, 1991; Zlokarnik, 1991).

In conventional aseptic processing, a number of dimensionless correlations have been proposed for the estimation of heat transfer under free and forced convection situations (Chandarana *et al.*, 1988; Zuritz *et al.*, 1990; Sastry *et al.*, 1990; Zitoun and Sastry, 1994ab; Awuah and Ramaswamy, 1996) and for the characterisation of the flow behaviour of food particles in the assembly of a pilot scale aseptic processing system

(Abdelrahim *et al.*, 1995a). Liu *et al.* (1992) described the behaviour of single solid particles with a density close to the liquid (water and CMC solutions) under turbulent and laminar flows in a tube. Correlations were obtained between the Froude (Fr) number, the Reynold (Re) number and the ratio of the particle velocity and the mean fluid velocity. For flow description, the relative velocity of a particle in a fluid is generally dependent on: 1) dimensionless numbers of particles and flow characteristics (e.g. Archimedes number (Ar_p), Froude number (Fr_p, Re_p); 2) dimensionless numbers of the fluid (Ar_f, Fr_f, Re_f); 3) relative size of particle to fluid and finally 4) ratio of particle to fluid density (Grabowski and Ramaswamy, 1995ab; Ramaswamy *et al.*, 1995; Ramaswamy and Grabowski, 1998).

For heat transfer situations, the Nusselt number (Nu) is usually correlated with other dimensionless numbers such as Grashof (Gr) and Prandtl (Pr) in free convection situations or Reynolds (Re) and Prandtl (Pr) in forced convection. Using Nusselt number (Nu), the heat transfer coefficient at the fluid/particle interface is obtained.

Until now, very few publications have mentioned the use of dimensionless numbers to describe the ohmic heating process. Natural convection driven by energy release from distributed volumetric energy sources appears to play an important role (Kulacki and Nagle, 1975; Kulacki and Emara, 1977; Fryer *et al.*, 1993). Ohmically heated fluids have been used to study natural convection. Fryer *et al.* (1993) correlated Nu as a function of Rayleigh number (Ra), which is a combination of Gr and Pr, to study heat generation and free convection effects in a static ohmic heating cell for liquid. A convection-modified thermal conductivity, based on Ra criterion, was used in solving the energy balance. A critical Ra was defined assuming that Nu is equal to 2. Poor fits were generally obtained when compared to experimental data. In order to improve the accuracy, they suggested that an electrical characteristic number (El) could be used to replace the Grashof number to model the electrically induced natural convection. El would be defined as (Fryer *et al.*, 1993):

$$El = \frac{\rho^2 \beta b d^2 \Delta T E^2}{\mu^2} \qquad [2.37]$$

Muller *et al.* (1994) investigated the behaviour of non-Newtonian liquids in a continuous collinear ohmic heater. They found that the heater design (liquid throughput, tube length and radius) is best characterised by the number of Graetz (Gz). Lower Gz indicated a better and more homogeneous temperature distribution. This would mean having a small radius, a longer tube and a very low liquid inlet flow.

Quarini (1995) studied the thermohydraulic behaviour of a liquid flowing into a vertical continuous ohmic heating column at steady state. Simplified momentum and energy differential equations were normalised and scaled to obtain dimensionless equations. Both Pr and Gr arise naturally from the momentum and energy equations. Q_p was defined as a non-dimensional volumetric heating term:

$$\underline{Q}_p = \underline{Q}\frac{R_o}{kS_a} \qquad [2.38]$$

S_a, is the axial stratification (K/m) for temperature, R_o, is the radius of the ohmic heating column, k, is the thermal conductivity and $\underline{Q}$, is the volumetric heating rate (W/m^3). The system of equations was solved numerically for a variety of conditions. However, it was not validated experimentally. At low volumetric heating rate and adiabatic walls, the flow distribution was parabolic for laminar flow and the temperature distribution was fairly flat as in usual forced convection. As the volumetric heating rate was increased, both the flow and temperature distribution began to change. The highest temperature occurred at the wall. The velocity profile was flat at the middle of the tube. The velocity rose to its peak at the centre of the tube before dropping to zero at the walls. If heating and flow rates were such that buoyancy became important, natural convection forces could dramatically change the flow and temperature distribution within the continuous ohmic heater. The aim should be to avoid temperature peaking of foods in regions of low flow. Possible means of enhancing uniformity were cooling of the containment walls of the column and designing desired conductive-temperature characteristics of foods. Indeed, the properties of the food were such that its resistance or conductivity to electrical current flow varied with temperature. One could anticipate a corresponding variation in volumetric heat generation but the exact variation depended on its intrinsic characteristics (thermal, physical and electrical). In order to establish a proper dimensionless correlation in ohmic heating processes either static or continuous, proper dimensionless numbers have to be identified possibly involving an electrical component.

REVIEW OF OTHER IMPORTANT FACTORS

Residence time distribution

The concept of residence time distribution has been recognised for a long time (Danckwerts, 1953). Solid/liquid two-phase flow has been discussed extensively with reference to long distance transport of mineral slurries. These studies mainly dealt with 1) high-density solids; 2) Newtonian carrier fluids; 3) small particle-to-pipe diameter ratios and 4) the predominance of turbulent flow conditions. Moving heterogeneous phases in a pipe will result in a residence time distribution in the liquid and solid phases (Manson and Cullen, 1974). Thus, the residence time distribution (RTD) is defined as the length of time that different elements spend in a system. Residence time of the fastest moving particle in the heating and holding sections of an aseptic system are critical from a public health standpoint. Lee and Singh (1990) demonstrated that particles can move faster than the average velocity of the liquid. Therefore, the problem assumes a high degree of importance with particulate foods because the fastest moving particle can dictate process design and the residence time distribution (RTD) of a two phase flow system must be considered as an integral part in the establishment of the thermal process. The importance of RTD of food particles processed in aseptic systems was emphasised by several studies for SSHE (Lee and Singh, 1991ac; Ramaswamy *et al.*, 1995a) and holding tubes (Dutta and Sastry, 1990; Lee and Singh, 1991b; Palmieri *et al.*, 1992; Abdelrahim *et al.*, 1997).

Several techniques have been developed for studying and investigating the RTD of solid/liquid two-phase flow (Yang and Swartzel, 1991; 1992). Ramaswamy *et al.* (1995b) reviewed the techniques for RTD measurement. Methods developed for studying the RTD of solid-liquid two-phase flow included visual observation, photography, playback videotaping, laser beam, radioactive tracer and magnetic response. Visual observation has been used to study the particle flow characteristics in some food systems (Toda *et al.*, 1979, Kim *et al.*, 1996b). McCoy *et al.* (1987) used the visual observation and stopwatch technique to study the residence time of simulated food particles in a transparent tube. Berry (1989) also used this technique with playback videotaping to study the RTD of particle suspensions in the holding tube. The visual observation method with the help of playback videotaping, stopwatch or photograph technique can only be used with transparent carrier fluid and tube. The laser beam technique was used by Ohashi *et al.* (1990) to measure local particle concentration and velocity in solid-liquid two-phase flow though vertical and horizontal tubes. They concluded that laser beam techniques yield more precise results than the photographic method. However, the costs of the optical equipment and laser beam signal processing system are high. The radioactive technique consists of using radioactive particles as tracers to investigate particle velocities in solid-liquid two-phase flow (Toda *et al.*, 1973). The main problem associated with this technique was the health hazard of radioactive materials and the limitation of the study to a single particle. The magnetic method is based on the detection of magnetic particles flowing in a stainless steel pipe. Segner et al. (1989) and Tucker and Richardson (1989) used this technique. The disadvantage was the use of only one particle at a time. Furthermore, the interaction between particles can not be investigated. The photoelectric sensor methodology was used to study the RTD of food particles in continuous flow thermal processing systems (Yang and Swartzel, 1991). Multiple sensor pairs installed around a transparent glass tube created a two dimensional optical-grid for detecting particle movement. As the particles passed through the optical-grid, they blocked the light beam and switched off the corresponding receivers. The main limitations of this method were the requirement for the use of transparent glass tube and carrier fluids. The residence time distributions of food particles in a heat treatment system can be studied using one of these different techniques. Most methods work well at low temperatures. Generally, the majority of published results was for a low proportion of solids with respect to liquid, which is a favourable situation to aseptic processing.

Residence time distribution is well described by an E and F function through the introduction of a tracer at the entrance of the system and enumerating them at the exit end (Levespiel, 1972). Inputs for RTD determination are step, pulse, sinusoidal, ramp and random sequence. Generally, the first two methods are used because of convenience and ease of mathematical analysis. The E function gives the RTD of the fluid and particles or exit age distribution for any non-ideal flow. It is defined as the fraction of material in the outlet stream that has been in the system between t and t + dt.

$$E(t) = \frac{C(t)}{\int_0^\infty C\,dt} \approx \frac{C(t)}{\sum_0^\infty C\Delta t} \qquad [2.39]$$

The F function is related to the E function by measuring the output response. It represents the accumulation of particles at the exit with a residence time of t seconds:

$$F(t) = \int_0^t E(t)\,dt = \frac{\sum_0^t C\Delta t}{\sum_0^\infty C\Delta t} \qquad [2.40]$$

Typical E and F curves for RTD are presented in Figure 2.4. For liquid foods, the RTD can be determined by injecting a tracer dye into the system at the entrance and measuring the change in the dye concentration with time at the exit. Other approaches use soluble salts (KNO_3, $NaNO_3$ and NaCl) or metal oxides (ZnO_2) as tracers that are subsequently analysed by conductivity or atomic absorption. It is virtually impossible to produce an exact step function experimentally, but it can be reasonably approximated by an input with a fast rise time compared to the process response time.

RTD for homogeneous fluid foods flowing in a typical aseptic system has been extensively studied for the scraped heat exchanger and the holding tube. RTD is influenced by various inter-related, interdependent factors originating from the food material and the processing. The fluid factors include: type, concentration, density, flow rate and rheological properties. The system factors comprise: temperature, pumping system, configuration of the heating device, holding tube length and diameter. The flow characteristics of a viscous food in the holding tube in any continuous thermal process lie within two extremes. A plug flow will result in a narrow distribution of the RTD. At the other extreme of a laminar flow, the maximum velocity of the fluid at the centre of the tube can be as much as twice the average velocity.

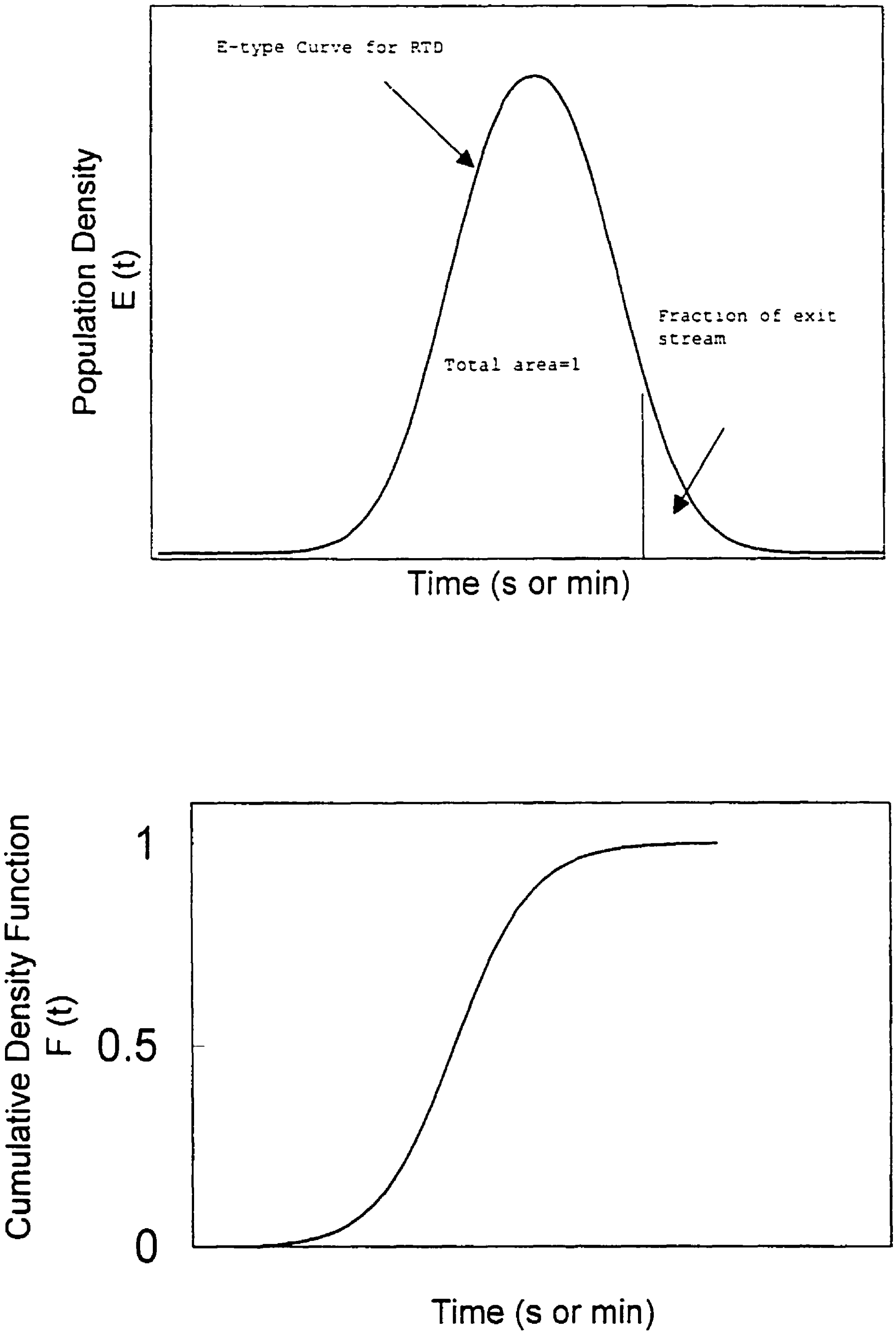


Figure 2.4 Typical E and F curves for RTD

Several studies on RTD in continuous sterilisation and pasteurisation systems of food have been reported (Chen and Zahradnik, 1967; Dickerson *et al.* 1968; Scalzo *et al.*, 1969; Milton and Zahradnik, 1973; Lin, 1979; Cuevas *et al.*, 1982; Heppell, 1985; Sancho and Rao, 1992; Abdelrahim *et al.*, 1993). Dickerson *et al.* (1968) and Scalzo *et al.* (1969) studied the residence time of milk (80 °C) and liquid egg (62 °C) using radioactive iodine. They concluded that the process calculation should be based on the fastest particle velocity in laminar flow to ensure proper pasteurisation. Rao and Loncin (1974) emphasised the importance of RTD in determining the length of the holding tube in aseptic flow systems.

Few experiments have been performed on the RTD of ohmic heating systems. RTD of particulates was investigated by Kim *et al.* (1996a) both visually and using a Hall effect magnetic sensor (Tucker and Withers, 1992) for a sauce (35 % total solids content). The flow characteristic was situated between a laminar flow limit and a plug flow. Although a plug flow situation is usually assumed for a high proportion of solids, Kim *et al.* (1996a) suggested using a laminar flow residence time limit as a conservative and safe practice. Velocity profiles are essential to obtain a clear understanding of the performance of the system and to perform process calculations. For example, product flow in pipes is considered either as plug, turbulent or laminar. Laminar flow is usually characterised by a Re number smaller than 2100. Although there is no specific value at which the flow regime changes from laminar to turbulent, a range of Re between 2000 and 3000 is commonly used to signify the transition zone between laminar and turbulent. In plug flow, all elements will flow at the same rate as a uniform mass. The velocity profile is flat. In laminar flow, the velocity profile of a Newtonian fluid is parabolic with the fastest element being at the centre of the pipe with its velocity about twice the average velocity. In the case of a fully developed laminar flow, the liquid velocity at any radial position r in a tube is given by:

$$v_r = \frac{2\dot{m}}{\pi R^2 \rho}\left[1-\left(\tfrac{r}{R}\right)^2\right] \qquad [2.41]$$

For turbulent flow, the fastest element is also at the centre of the pipe at 1.25 times the average velocity. All of these regimes are determined through the rheological properties of fluids, which depend on processing conditions. Unfortunately, not much is known on the viscosity of food fluids.

Rheological properties of fluids

Rheological properties will influence the velocity profiles in the system (Steffe, 1992). A continuous ohmic heating column as designed by APV can be described as a flow in an ordinary pipe or holding tube. Palmer and Jones (1976) demonstrated that the estimation of the holding tube length in aseptic processing was influenced by the rheological properties of the liquid medium (Newtonian vs. non-Newtonian). Based on laminar or turbulent flow conditions, a microbiologically safe design criterion would be ensured for Newtonian fluids and shear-thinning liquids but not for dilatant (Rao, 1992).

The rheological properties of the fluid are required for fluid mechanics studies in order to characterise the flow nature (Holdsworth, 1971) as the fluid travels through the continuous ohmic heating system. Flow regime specification (laminar, transition or turbulent) requires the calculation of the Reynolds number, which is a measure of the ratio of the inertial force to the force of internal friction (viscosity). The rheological behaviour of matter, that flows, is characterised by the measurement of viscosity that is defined as the internal friction or resistance experienced by the fluid as it moves over another layer of the fluid.

Lethality evaluation

Similar to other situations involving continuous sterilisation, the critical consideration is the prediction of cold-spot temperatures during the process. The time for which food is processed is calculated using the requirement that a certain level of lethality must be applied to the whole material. The time that the product spends in the holding tube of an aseptic processing system and the processing temperature dictate the lethality of the process. The accumulated or integrated lethality is calculated using the conventional F_0-value:

$$F_0 = \int_0^t 10^{(T-T_{ref})/z}\, dt \qquad [2.42]$$

Where T is the temperature as a function of time (t) at the coldest location and Z is the negative reciprocal slope of the logarithmic thermal death time (TDT) or D curve versus T. The "decimal reduction time", D, is the time for a reduction of micro-organisms by 90%. T_{ref} is the reference temperature. The objective is therefore to determine the coldest-location temperature, which will allow one to calculate the accumulated lethality sufficient to provide a microbiologically safe product.

In the absence of any physical means for temperature measurement, biological evaluation is the alternative available to evaluate the lethality delivered at the cold point during ohmic heating. Biological validation can be performed in several ways. The utility of several indicators including immobilised peroxidase, thiamine, methylmethionine sulphonium, trypsin, *Bacillus stearothermophilus, Bacillus anthracis, Bacillus subtilis* and *Clostridium sporogenes* have been demonstrated (Weng *et al.*, 1991; Mulley *et al.*, 1975; Berry *et al.*, 1990; Awuah *et al.*, 1993; Sastry *et al.*, 1988; Hunter, 1972; Abdelrahim, 1994; Brown *et al.*, 1984). Moreover, the FDA requires inoculated-pack validation for aseptic processing of viscous low acid liquid foods containing particles (Dignan *et al.*, 1989). Pflug *et al.* (1990) discussed the advantages and disadvantages of using different methods in the biovalidation of aseptically processed foods. Immobilisation of indicators in a matrix of alginate/food puree forming a particle was one of the techniques. Incorporation of magnets, markers or micro-organisms at the centre of these particles is used to study residence time distribution, heat transfer at the interface between the particle and the liquid or process lethality of the aseptic system (Segner *et al.*, 1989; Dallyn *et al.*, 1977; Gaze, 1989; Gaze *et al.*, 1990). The use of these simulated particles has the advantage of offering a certain flexibility and control in the size and the shape of particles facilitating the incorporation of indicators. Brown *et al.* (1984) used the immobilisation technique for large particles (0.8-2.4 cm). However, significant differences were found between experimental and calculated lethality attributed mainly to properties of food/alginate particles. Abdelrahim (1994) found high thermal sensitivity of *Bacillus subtilis* at elevated temperatures that was attributed to some of the effects of chemical ingredients used in the fabrication of immobilised bioindicator particles. According to Russell (1982) some divalent metallic cations can affect the heat resistance of bacterial spores. In fermentation processes using encapsulated *Propionibacterium shermanii* immobilised in alginate beads, it has been demonstrated that calcium chloride used in high concentration reduced the efficiency of the production of propionate (Begin *et al.*, 1995). Precautions must be taken not to affect the bioindicator.

Parrot (1992) generated the first microbiological data from lethality challenge tests using spores of *Bacillus stearothermophilus* embedded in alginate analogues of beef and carrot. It was found that alginate particles received similar F_0 values to that of the fluid. These values were also similar at the centre of a large particle and throughout the particle suggesting that lethality was probably uniform.

Kim *et al.* (1996a) investigated the lethality within food particles undergoing ohmic heating using both microbiological and chemical marker measurements. Meatballs at 30-40 % solids concentration in a starch solution were processed using a 5 kW ohmic system to study the effect of different temperatures, flow rates, holding tube length and fluid electrical conductivities. Observed lethalities were reported to be consistent with predictions. Higher lethalities were found at the centre of meatballs rather than near the surface. The results suggested that the sterility of ohmically heated particulate foods might be evaluated, as a first approximation, based on the fluid temperature and the residence time (ratio of holding tube geometry to flow rate).

VALIDATION OF AN OHMIC HEATING PROCESS

Thermal process calculation for ohmic heating should be based on the worst case scenario. The ohmic heating situation is less familiar when compared to conventional sterilisation processes and requires new skills from the food technologist and chemical engineer (Larkin and Spinak, 1996).

Sastry (1991) summarised the following important issues to be considered during the establishment of an ohmic heating process. Electrical conductivities of solid and liquid phases and their temperature coefficients should be closely matched. If the solid phase is of lower electrical conductivity than the liquid phase, particle concentration plays a critical role. High particle concentrations will result in faster heating of the solids but slower overall heating. The lowest electrical conductivity particle in the mixture of highest conductivity liquid should be identified as a potential candidate to result in underprocessing. As well, particle orientation is extremely important if the particle aspect ratio is far from unity. A particle oriented parallel to the electrical field permitting a maximum current by-pass and having a minimal cross-sectional surface area exposed to the current will heat slowest. For cubic and spherical particles, the effects are relatively small. Particle size has a minor effect on heating rates. RTD and fluid-to-particle heat transfer coefficient have effects that are less significant than in conventional processing. A low heat transfer coefficient is a conservative assumption. Finally, the RTD of the fastest particle should be used.

A procedure has been suggested (Fryer and de Alwis, 1989) by which an ohmic process can be confirmed in terms of safety and product quality: 1) find the electrical conductivity of all the components as a function of temperature and measure their heating rates under static conditions as a function of their orientation to the electric field; 2) identify the worst-case particle that heats slowest. The process parameters are set to sterilise the worst-case in the worst orientation; 3) carry out tests to determine the effect of the process on the fastest heating component to check for unwanted degradation and finally 4) perform additional tests on any component known to be thermally labile.

Sastry and Salengke (1998) analysed the risks of the situation, which would represent the worst-case scenario in ohmic heating. Worst cases are scenarios when a single particle is of lower temperature than the surroundings. This would occur when there is 1) an inclusion particle of lower electrical conductivity or 2) an inclusion particle of higher electrical conductivity. The current bypass scenario that can occur in case of small particles or an orientation that minimises the cross-sectional surface area to the electric field was found to be the most critical and difficult to control. There is a potential for underprocessing for inclusion of such low electrical conductivity particle. For that situation, convection should be included in the model. Unlike conventional heating, in which fluid motion is necessary for improved heating, internal heat generation processes have the potential for runaway heating at selected locations and fluid motion has the effect of dissipating the heat and serves to moderate the heating rather that to enhance it.

OHMIC HEATING OF VISCOUS LIQUIDS

Little information is available on ohmic heating of viscous liquids although these are frequently used either as carriers for particulate foods or as such in viscous products like sauces or puddings.

Hydrocolloid solutions

The class of food components that have the ability to increase the viscosity or form a gel in aqueous systems (Imerson, 1992) are identified as gums, hydrocolloids, thickening or gelling agents, or stabilisers. The viscosity producing effect is common to all hydrocolloids but only a few have also the ability to form gels (Rao, 1977). In addition, hydrocolloids have many secondary functional properties (for example, to stabilise food emulsions or proteins, to suspend insoluble particles etc.). Hydrocolloids impart viscosity to the aqueous phase to provide texture, body and mouthfeel (Rosett *et al.*, 1996; Szczesniak, 1985). There is a relationship between the viscosity and gelling characteristics of many hydrocolloids. Certain hydrocolloids can be used as thickening agents at low concentration while they become a gelling agent at high concentrations. An interesting characteristic is that all hydrocolloids give fairly high viscosities at very low concentrations.

Basically, food-grade hydrocolloids are derived from the following sources: plant exudates, extracts and flours, microbial fermentation or biosynthesis, chemical modification or synthesis (Glicksman, 1982a). Hydrocolloids are extracted from algae (agar agar, carrageenan, furcellaran, alginic acid and alginates), plant (pectin and pectic salts, cellulose and cellulose derivatives) or seeds (guar, carob and tara). The earliest known hydrocolloids are plant exudates (gummi arabicum, tragacanth and karaya). Such hydrocolloids like starches, guar and locust bean gums are mechanically separated from the cereal or plant seed to obtain a fine powder or flour. These food-grade compounds can also be modified chemically. Microbial fermentation or biosynthesis can also be used to produce polysaccharides used as gums such as xanthan or gellan.

Hydrocolloids are high molecular weight polymers. Some hydrocolloids can be anionic, acidic or neutral which may affect the efficiency of the ohmic heating process. For the most part (i.e. except for gelatin), hydrocolloids are carbohydrates, known as polysaccharides or polymers composed of simple sugar-building units that are incorporated in food systems (Dziezak, 1991). These polymers are either linear or branched. Some polysaccharides are naturally anionic, possessing acidic function such as carboxyl, sulphated or phosphate groups. Others possess amino groups which are usually monoacetylated or sulphated. Such polysaccharides may show cationic properties. These anionic, acidic or neutral states of hydrocolloids may affect their efficiency and stability in a specific food formulation. The following is some relevant information about some hydrocolloids commonly used in the food industry.

Carrageenans are obtained from red seaweed extraction in alkaline solution. Extracts of red seaweeds compose a family of hydrocolloids including agar, furcellaran and three types of carrageenan (Glicksman, 1983). The latter are linear chains of polysaccharides and must be heated to dissolve. It consists of sulphate esters of galactose and 3,6-anhydro galactose. There are three kinds of carrageenans: iota, kappa and lambda carrageenan. Kappa carrageenan forms a gel on cooling in the presence of potassium ions or proteins while iota carrageenan requires the presence of calcium ions to form a gel, but lambda carrageenan is incapable of forming a gel. Carrageenan is considered as an acidic gum. It is generally used to give body and thickness to yoghurt; pudding and milk based products because of its ability to stabilise caseinate in milk products. Kappa carrageenan is usually used with locust bean gum in clear water dessert gels to provide a more gelatin-like texture and to increase syneresis. The best known synergistic carrageenan interactions are those involving milk proteins. Iota carrageenan, in combination with starch, also produces a body equivalent to 4 times that of starch alone.

Xanthan was the first of new generation of polysaccharides, produced by biotechnology concepts (Kelco, 1994). Xanthan gum was developed in the USDA laboratory in Peoria, Illinois in the early 1960's. The gum is a microbial exopolysaccharide, which is produced by *Xanthomonas campestris* in pure culture fermentation. The FDA first approved it in 1969. This gum is an heteropolysaccharide of high molecular weight, which is substituted on its linear chain. The polymer backbone consists of (1-4) linked β-D-glucose. Therefore, it is identical to cellulose. There is a side chain that occurs every alternate residue and it consists of units of two α-D-mannose and one β-D-glucuronic acid. The presence of the glucuronic acid units or carboxyl groups on these side chains renders the gum molecules anionic but it can be neutralised by cations such as $Na+$, $K+$ and $Ca++$. It is very stable at high temperatures. As well, in the presence of salt or acid, the stable molecular structure persists. It can be easily dissolved in hot and cold water. It is commonly used for milk based products as a viscosity enhancer. In the absence of shear, the rigid molecules interact transiently to produce a gel-like structure and hence high viscosity at low gum concentrations.

Pectin, a component of the cell wall of all plants, has a natural image (Christensen, 1982; King, 1991). Pectins are usually obtained from the fibrous and pulpy part of citrus or apple pommace. It is a polymeric carbohydrate composed of a chain of galacturonic acid units. The galacturonic acid chain is partially esterified as methyl esters. The degree of esterification (DE) indicates the percentage of galacturonic acid units in the methyl ester form and it determines the functional properties of pectin. Pectins form a gel at low pH and a high proportion of soluble solids. As the DE is increased, less soluble solids are necessary for gel formation. As well, the gel can be obtained at higher pH. The gelling power of pectin has been used in foodstuffs since the first fruit preserves were made. It is usually used in fruit based systems or jams, filling and fruit sauces. High methoxyl esters pectins are used to achieve gel formation in fruit-based systems. However, it will gel only under specific conditions of sugar concentration and acidity (Da Silva and Rao, 1995). Therefore, they are best suited for fruity products. Low methoxyl pectins form gels by reaction with calcium ions. Because milk products contain calcium, they can be easily be gelled using low methoxyl pectins. Pectin is a negatively charged hydrocolloid and as such interacts with positively charged polymers in solution.

Gelatin is often regarded as a member of the gum family in spite of being a totally digestible protein rather than a polysaccharide. It is a widely used gelling agent

(Sanderson, 1996). Gelatin is defined as a product obtained by partial hydrolysis of collagen, the primary protein component of animal connective tissues (e.g. skin, bone and tendon). It is a mixture of protein molecules of similar structural type. Building blocks are different than for polysaccharides. Gelation is due to hydrogen bonding between two amino acid residues by the elimination of a water molecule. Gelatin has to be heated in solution to be dissolved. In the food industry, gelatin is one of the hydrocolloids or water-soluble polymers that can be used as a gelling, thickening or stabilising agent. The most commercially popular use of gelatin is the famous "Jello", developed by a citizen from New York in 1897. Since then, it has found many applications in confectionery, dairy and meat industry. It is very sensitive to pH and as the salt content is increased, there is less variability in gel formation.

Starch is by far the most widely used hydrocolloid in the food industry. It is the energy reserve polysaccharide in plants. Starch is composed of glucose units, which can be either linearly linked through a carbon α-1-4 to form amylose, or the linear chain can be branched to form amylopectin. Most starches are usually a combination of amylose and amylopectin in different proportions. It is a neutral hydrocolloid. They are many types of starches, derived from corn, wheat, potato, tapioca, rice and many other sources. Most common starches are obtained from corn. Starch can be modified to obtain particular properties. Corn starch can be modified to provide stability at high acidity, high temperature and upon thawing. It is widely used in food systems.

To render the hydrocolloid or gum functional, they must be hydrated in water. This is often referred to as solution preparation (Sanderson, 1996) although gums form hydrocolloidal dispersions rather than solution. For effective hydration, each individual particles of the dry powder must be separated or dispersed. To achieve a good dispersion, an efficient mixer is used or alternatively the gum is mixed with other dry ingredients in food formulations. Once the dispersion is completed, hydration can take place. Hydration usually requires a heat treatment.

The utility and importance of hydrocolloids in food systems is based on their functional properties (Glicksman, 1982b). The useful properties of these compounds are due largely to physical effects, primarily those dealing with their interaction with water.

Rheological properties

Rheological characteristics are a useful aid to the selection of the proper hydrocolloid for a specific food application (Marrs, 1996). The selection process of a particular hydrocolloid in a food formulation depends on many factors. Desirable rheological characteristics are mainly influenced by their concentration in water and usually vary with temperature in a specific pattern. External factors such as the pH, amount of soluble solids and amount of proteins will also influence the selection of the proper hydrocolloid in a specific food formulation. It is well known that pH levels will determine the choice of hydrocolloids (Przybyla, 1987).

In addition to these properties, hydrocolloids have many secondary functional properties (ex: to stabilise food emulsions or proteins, to suspend insoluble particles etc.). Hydrocolloids are not only good at giving proper product quality but also very important in food processing unit operations. These compounds play an important role in the transportation of solid particles in aseptic processing equipment (Palmer and Jones, 1976; McCoy *et al.*, 1987; Berry, 1989; Lee and Singh, 1991abc; 1993; Dutta and Sastry, 1990; Abdelrahim *et al.*, 1995b) including ohmic heating (Khalaf and Sastry, 1996; Kim *et al.*, 1996a). Flow characteristics of pumpable liquid, viscous and semi-liquid foods are dependent on the fluid viscosity and density. Therefore, knowledge of food system rheological properties is essential for the design, evaluation and modelling of continuous processes. It has been recognised that rheological properties of hydrocolloids in solutions depend on many factors: concentration of the active compound, temperature, degree of dispersion, solvation, electrical charge, previous thermal and mechanical treatment, presence or absence of other lyophilic colloids, age of the lyophilic solution and the presence of electrolytes and non-electrolytes.

Rheological properties of these fluids also depend on the shear rate or shear stress, the duration of the shear as well as the previous shear history (Rao, 1977). During ohmic heating, carrier fluids will be subjected to different shear rates in different sections of the system. Usually, low shear rates will be observed in straight holding tubes and high shear rates while passing through pumps. Solutions of hydrocolloids are usually known to be non-Newtonian, generally pseudoplastic fluids (Rha, 1978), which means that their apparent viscosity decreases when the shear rate is increased or that the fluid is shear thinning.

Depending on the flow behaviour under imposed shearing forces, fluids can be classified into two main categories: Newtonian and non-Newtonian. For Newtonian, the fluid maintains a constant consistency irrespective of the shear rate. Non-Newtonian fluids can be further classified into three main categories: time-independent, time-dependent and viscoelastic flows. For time-independent flow, the shear stress depends only on the shear rate whereas for time-dependent the shear stress can be a function of magnitude and duration of the shear rate as well as the time lapse between two consecutive applications of the shearing. Finally, the fluid exhibiting the property of partial elastic recovery upon removal of the shearing stress is viscoelastic.

Time-independent flow

Most viscous food liquids are non-Newtonian in nature. They do not exhibit a linear relationship between the shear stress and the shear rate. These fluids can be further characterised as plastic, pseudoplastic (or shear thinning) or dilatant (or shear thickening). Several models have been used to represent the flow behaviour of hydrocolloid solutions. Four models: linear (Newtonian or Bingham), power law (Ostwald-de-Waele), power law with a yield (Herschel-Bulkley) and Casson are generally found to be satisfactory to describe the flow behaviour of solutions of hydrocolloids. One of the early models, which characterised the shear stress/shear rate behaviour for a fluid exhibiting a yield stress, was the Bingham Plastic. The Casson model relates the square root of shear stress to the square root of shear rate and has been found to be particularly suitable to describe chocolate rheology. Other models (e.g. Powell Eyring and Ellis) have been developed to describe the flow behaviour of shear thinning fluids based on a zero shear and an infinite shear viscosity.

The power law model or Ostwald-de-Waele is usually preferred because of its compatibility with engineering calculations (Lalande *et al.*, 1991) and for time-independent fluids, it is the most widely used rheological model to represent the data:

$$\tau = m\dot{\gamma}^{n} \qquad [2.43]$$

The viscosity, which changes with the shear rate, is termed apparent viscosity η_a. The term apparent implies a Newtonian type of measurement to a non-Newtonian system and therefore must be specified with respect to a shear rate:

$$\eta_a = \frac{\tau}{\dot{\gamma}} = m\dot{\gamma}^{n-1} \qquad [2.44]$$

In the presence of a yield stress, the power law becomes the Herschel-Bulkley model:

$$\tau = \tau_0 + m\dot{\gamma}^{n} \qquad [2.45]$$

A yield stress is the minimum stress necessary to cause the fluid to flow. The yield stress is usually determined by extrapolation of the flow curve to zero shear rate.

Effect of temperature

As well, different temperatures are usually encountered during processing of hydrocolloid solutions, therefore, their rheological properties are studied as a function of temperature. The effect of temperature on both the consistency coefficient (m) and the flow behaviour index (n) can be evaluated using the Turian approach (Turian, 1964) as in Equations [2.46] and [2.47] respectively:

$$\log m = \log m_0 - A_1 T \qquad [2.46]$$

$$n = n_0 + A_2 T \qquad [2.47]$$

An Arrhenius-type of equation is also frequently used to describe the effect of temperature on the (apparent) viscosity of (non-Newtonian) Newtonian fluids (Scott-Blair, 1969):

$$\eta_a = \eta_0 e^{\left(\frac{-E_a}{RT}\right)} \qquad [2.48]$$

η_0 is the frequency factor that is also an apparent viscosity under specific shear rate conditions. Speers and Tung (1986) have used this method. They regressed the logarithm of apparent viscosities vs. the reciprocal of the absolute temperature at a specified shear rate to calculate the frequency factor at various concentrations. However, Abdelrahim *et al.* (1994) found that it was the best model to use for Thermo-flo starch especially at lower concentrations.

Effect of concentration

The effect of concentration of viscous suspensions is generally described by either an exponential or a power relationship (Rao, 1986; Speers and Tung, 1986):

$$\eta_a = \eta_0 \, e^{X_1 C} \qquad [2.49]$$

$$\eta_a = \eta_0 \, C^{X_2} \qquad [2.50]$$

Time-dependent flow

Hydrocolloid solutions may also exhibit time-dependent properties, mainly thixotropy, which means the apparent viscosity, or consistency will decrease with time. Time-dependent flow can be further divided into thixotropic and rheopectic flow. For thixotropic flow, there is a reversible decrease in shear stress with time whereas the time dependent loss of structure is not recoverable for rheopectic fluids. The general approach used to characterise the time dependent flow is either 1) to evaluate the stress decay under a steady shear over a specified period of time or 2) to measure the hysteresis loop i.e. the areas between the upward and downward curve with a programmed shear rate as a function of time. The first method gives the most complete information and is easy to perform experimentally. Weltmann (1943) proposed a model to describe the time decay of the shear stress under a constant shear describing the shear thinning behaviour. A modified version of the Weltmann model (Ramaswamy and Basak, 1991) is shown:

$$\tau = \tau_m - B_m \log\left(\frac{t}{t_m}\right) \qquad [2.51]$$

This model describes the continual stress decay, without reaching an equilibrium state even at prolonged shear. A second model was developed by Hahn *et al.* (1959) to include an equilibrium shear stress that followed the first order type relationship:

$$\log\left(\tau - \tau_e\right) = B_1 - B_2\, t \qquad [2.52]$$

Abdelrahim *et al.* (1994) and Ramaswamy and Basak (1992) used a modified Weltmann logarithmic model to describe the thixotropic behaviour of CMC solutions and pectin in flavoured yoghurt respectively.

Based on rheological properties of viscous liquids, multiple regression analysis is used to generate parameters necessary to quantify the effect of non-Newtonian flow behaviour, temperature, concentration and time dependency. Rheological characteristics of viscous liquids will influence the ohmic heating process affecting the flow and the heating behaviour.

Viscoelastic flow

A viscoelastic fluid has the properties of and elastic (solid like) and viscous (liquid like) fluid simultaneously. A partial recovery is obtained once the stress is removed. This flow behaviour is also time dependent but differs from thixotropic fluid as non-instantaneous. This dual nature is evident for some fluids and semi-solids such as flour dough, cake batter, melted cheese, honey and aged condensed milk.

Effect of rheological properties on velocity profiles

The maximum fluid velocity (v_{max}) and the mean fluid velocity (v_{mean}) in the ohmic heating tube flow are dependent on the flow behaviour index (n) of the flowing fluid and the flow regime:

$$v_{\max} = \left[\frac{3n+1}{n+1}\right] v_{mean} \qquad [2.53]$$

For a pseudoplastic fluid, n < 1, $v_{max} < 2\ v_{mean}$ whereas for a dilatant fluid, n > 1 and $v_{max} > 2\ v_{mean}$ under laminar flow conditions. The radial distance in the holding tube in addition to the rheological properties influences velocity profiles. Mathematically, the velocity of a fluid at any specific radial location in tube flow can be estimated from the following relationship:

$$\frac{v}{v_{mean}} = \left(\frac{3n+1}{n+1}\right)\left[1-\left(\frac{r}{R}\right)^{\frac{(n+1)}{n}}\right] \qquad [2.54]$$

Thermal properties of hydrocolloid solutions

Knowledge of thermal properties is important to properly design thermal processing equipments. Larkin (1989) conducted simulations on heat transfer to particles in conventional continuous sterilisation systems. He observed that assumed values of thermal properties played a significant role in the results. Therefore, it can be extended that accurate data on thermal properties must be obtained under processing conditions of ohmic heating to properly predict or calculate a heat treatment schedule with mathematical ohmic heating models. A number of methods are available to predict thermal properties. Murakami and Okos (1989) have provided an extensive review of this subject. Despite the fact that models have been developed for thermal properties to give a good approximation, it is usually suggested to measure them experimentally for each particular case.

Thermal conductivities of foods typically range between a low value greater than that of air (k = 0.023 W/m°C) and a high point slightly below that of water (k = 0.6 W/m°C). Most experimental techniques for thermal conductivity measurement require large food samples. Sweat *et al.* (1974) developed a line source probe for small samples (2.54 cm). Nowadays, this technique is commonly used and is generally recommended.

Another parameter having a significant impact on heat transfer calculations is the specific heat (C_p). Specific heats are easier to measure than thermal conductivity with sophisticated techniques such as differential scanning calorimetry (Rahman, 1995b).

Ohmic heating of hydrocolloid solutions

Little experimental work has been performed on ohmic heating of single-phase viscous fluids. However, results have been reported for mixtures of viscous liquids containing particulates during ohmic heating (de Alwis *et al.*, 1989; Khalaf and Sastry, 1996; Kim *et al.*, 1996a; Fryer *et al.*, 1993; Orangi and Sastry, 1998).

De Alwis *et al.* (1989) reported that enhanced heating rates of viscous liquids are observed due to the higher temperature coefficients of electrical conductivity as compared to low viscosity solutions. As well, heating rates of liquids were found to increase with field strengths, the effect being more important for high electrical conductivities.

Fryer *et al.* (1993) reported that when a wooden cylinder, treated as a particle, is heated up in an electrically conductive fluid, the fluid heating rate increases with the fluid viscosity. They attributed this phenomenon to a lack of convection in a high viscosity fluid, which yield to high temperatures in regions of maximum current density.

Khalaf and Sastry (1996) investigated the effect of fluid viscosity on ohmic heating rates of identical electrical conductivity solid-liquid mixtures with high proportions of solids (>30 %) under batch (static and vibrating) as well as continuous flow conditions. Studies were conducted using varying concentrations of CMC to vary the viscosity and sodium chloride to adjust the electrical conductivity. For batch heater experiments, heating rates of fluid and particles were comparable for different fluids of identical electrical conductivity but different viscosity. In a vibrating ohmic heater, the heating rate was found to increase with increasing fluid viscosity. Finally, in the continuous flow heater, the mixture with the higher viscosity fluid heated faster than that with the lower viscosity fluid. They suggested that poor interphase convective heat transfer might actually contribute to accelerate overall heating. The more conductive phase does not lose heat readily to the less electrically conductive phase. Therefore, it heats rapidly transferring heat to the other phase by larger temperature differences. Their results indicated that in ohmic heating, unlike conventional heating, the use of viscous carriers could actually enhance heating rather than retard it.

In their investigation of continuous flow ohmic heating of solid-liquid mixtures, assuming a pseudoplastic fluid with a flow behaviour index of 0.3, Orangi and Sastry (1998) found a thermal inversion wherein the low electrical conductivity phase which initially heats slowest, begins to heat faster than the phase of higher electrical conductivity.

CONCLUSION

This review of literature revealed that many questions regarding the application of ohmic heating especially to viscous liquids have not been answered. In particular, there are very few data on electrical conductivity of viscous hydrocolloid solutions that have been reported in the context of ohmic heating. Are some hydrocolloids more efficiently heated during ohmic heating ? What would be the effect of adding charged compounds like salts and acids to these hydrocolloid solutions on their ohmic heating behaviour ? As well, ohmic heating has not been compared to conventional heating treatments. Moreover, little is known on the continuous ohmic heating process for viscous hydrocolloid solutions. Models have been developed but not validated experimentally. What would be the effect of rheological properties on the ohmic heating behaviour of these solutions ? Clearly, more work needs to be done in these areas.

CHAPTER 3

ELECTRICAL CONDUCTIVITIES OF HYDROCOLLOID SOLUTIONS

CONNECTING STATEMENT

From the review of literature, it was obvious that little work has been done on electrical conductivity measurements and ohmic heating behaviour of viscous liquid foods.

The study undertaken in this chapter was aimed at investigating the effect of hydrocolloid types and concentrations in water on electrical conductivities generated in a static cell in order to gather and compare values in the context of ohmic heating i.e. low voltage alternating current.

This following manuscript has been published based on material presented in this chapter: Electrical conductivities of hydrocolloid solutions. 1998. *J. Food Process Eng.* **21:** 503-520. The authors are: Michèle Marcotte (Ph.D. Candidate, who planned and conducted experiments, analysed results and wrote the manuscript), Hosahalli Ramaswamy (thesis supervisor, who guided the student, corrected, edited and reviewed the manuscript), Gabriel Piette (who corrected and reviewed the manuscript).

ABSTRACT

Ohmic heating was applied to solutions of 5 hydrocolloids (carrageenan, 1-3 % w/w; xanthan, 1-3 % w/w; pectin, 1-5 % w/w; gelatin, 2-4 % w/w and starch, 4-6 %w/w) in a static cell to study the effect of concentration and temperature on electrical conductivities. For each experiment, the sample was poured into the cell and heated using a constant voltage gradient of 7.24 V/cm. Voltage, current, time and temperature were logged at selected intervals and used to calculate electrical conductivities as a function of temperature. Of the thickening agents examined, carrageenan gave the highest value for electrical conductivity (0.2 S/m at 25 °C and 1% and 1.4 S/m at 100 °C and 3 %) followed by xanthan (0.14 S/m at 25 °C and 1 % to 1.1 S/m at 100 °C and 3 %). Pectin and gelatin samples were found to exhibit lower, but similar electrical conductivities (0.06 S/m at 25 °C at the lowest concentration to 0.37 S/m at 100 °C at the highest concentration). Starch samples had the lowest electrical conductivity varying from 0.05 S/m at 25°C and 4 % to 0.21 S/m at 100 °C and 6 %. Regression equations were established for each hydrocolloid revealing a strong interaction between concentration and temperature on electrical conductivity values. Major differences were observed between hydrocolloid types on electrical conductivities that were mainly attributed to their ash content.

INTRODUCTION

Ohmic heating is a rapid method of heating that could replace conventional heating processes for liquid foods with or without added hydrocolloids (Parrot, 1992). To optimally design such a process, data on electrical properties of foods are essential (de Alwis and Fryer, 1992). Most research on electrical properties of foods have focussed on the mechanisms of interaction between the food and the electromagnetic energy under microwave and radio-frequency heating conditions (Mudget, 1992). Food materials have been reported to have a wide range of electrical conductivities from 10^{-3} to about 10^{2} S/m (de Alwis *et al.*, 1989; Stirling, 1987), between conducting materials and insulators.

Interest in the measurement of electrical conductivity has mainly centred around solid food particles (Mitchell and de Alwis, 1989; Halden *et al.*, 1990; Palaniappan and

Sastry, 1991a) mainly due to the industrial breakthrough of the APV Baker Ohmic Heating Technology for aseptic processing of low acid fluids containing particulates. Discrepancies have been reported with respect to the magnitude of the electrical conductivity of solid particles (Palaniappan and Sastry, 1991a). A large amount of published data on electrical conductivities have been reported at room temperature as they have been investigated as quality control measures to evaluate physiological processes during growth occurring in plant tissues (Sasson and Monselise, 1977; Bean *et al.*, 1960; Weaver and Jackson, 1966).

Ohmic heating of liquid foods has not been studied in as much detail as solids (Fryer *et al.*, 1993) and only a few reports have been published (Palaniappan and Sastry, 1991b; Kim *et al.*, 1996a; Fryer *et al.*, 1993; Khalaf and Sastry, 1996). Electrical conductivities of liquids are commonly measured with meters that operate at frequencies at or above 1 kHz (Mitchell and de Alwis, 1989; Kim *et al.*, 1996a; Fryer *et al.*, 1993). However, it has been shown that for fluids with a high concentration of dissolved or entrapped ions, the electrical conductivity is a strong function of the frequency (Falkenhagen, 1934). This was also confirmed by Imai *et al.* (1995) during ohmic heating of Japanese white radish. The frequency of the meters is usually chosen in order to avoid polarisation in cells and capacitive errors in measurements. Electrical conductivity of liquids is generally higher than that of solids (< 0.5 S/m). Typical values ranging from 0.50-1.6 S/m over a temperature of 20-80 °C have been reported for low viscosity liquids such as orange, tomato and carrot juices (Palaniappan and Sastry, 1991b). Considerable data are available for milk but under high temperature conditions because it has been mainly used as a test for mastitis in cows (Datta *et al.*, 1984).

Little has been published on the electrical conductivity of viscous fluids, which are normally used as carrier liquids in conventional aseptic processing and ohmic heating. According to Kim *et al.* (1996a), the salt content of a typical gravy used for a beef stew is between 0.6-1.0 %. A sauce of 5.5 % starch with 0.55 % salt will have an electrical conductivity of 1.3 S/m. This value is considerably greater than the electrical conductivity of solid food particles. In fact, Sastry (1992b) has pointed out that more information is needed on electrical conductivity for a wide variety of carrier fluids.

Currently, a number of hydrocolloids are available for specific food formulations. Therefore, the objectives of this work were 1) to measure electrical conductivities of aqueous solutions of selected hydrocolloids (xanthan, carrageenan, pectin, gelatin and starch) as a function of their concentration over a temperature range of 20-100°C, 2) to determine and model the effect of temperature and concentration on electrical conductivities of these solutions and 3) to compare the different hydrocolloids based on their electrical conductivity values.

MATERIALS AND METHODS

Choice of hydrocolloids

Five specific hydrocolloids were chosen in this study which possess different structural and compositional characteristics: carrageenan, xanthan, pectin, gelatin and starch. Since polysaccharides (homo or heteropolysaccharides) are the largest category of hydrocolloids, the selection included 4 polysaccharides.

Hydrocolloid solution preparation

Samples of five commercial hydrocolloids: carrageenan (Grinsted Carrageenan, CL210, Danisco Ingredients Canada, Rexdale, ON, Canada), xanthan (Rhodigel, lot # 9635001, Rhone-Poulenc Food Ingredients, Washington, PA, USA), pectin (Grinsted Pectin, RS400 lot # 701J547, Danisco Ingredients Canada, Rexdale, ON, Canada), gelatin (Gelatin, type B 250 bloom, Germantown Canada Inc., Scarborough, ON, Canada), starch (Thermo-flo starch, NFPA 0934 lot # LF5919, National Starch and Chemical Corp., Bridgewater, NJ, USA) were obtained. Three levels of concentration for each hydrocolloid were prepared in distilled water: carrageenan (1, 2 and 3 % w/w), xanthan (1, 2 and 3 % w/w), pectin (1, 3 and 5 % w/w), gelatin (2, 3 and 4 % w/w), starch (4, 5 and 6 % w/w) to obtain 500 ml of solution. Hydrocolloids were dispersed using a high-speed blender for 8 min at high temperature (80 °C). Then, the dispersions were centrifuged (Centrifuge, Model GS-6, Palo Alto, CA, USA) at 2000 rpm for 5 min to remove entrapped air bubbles and cooled. Each solution was prepared in duplicates to be used in the ohmic heating experiment.

Ash content

The ash content was measured using the dry ashing method (AOAC, 1984). First, powdered hydrocolloids were weighed accurately and dried for 6 h in a vacuum oven at 70 °C. Samples were weighed again and the moisture content was determined. Then, samples were burned in a muffle furnace (Pyradia, Model 3001, Longueuil, QC, Canada) at 525 °C for 24 h and weighed again. The ash content was calculated on a dry weight basis based on weight difference. Measurements were performed in duplicate.

pH

The pH of hydrocolloid solutions was measured using a pH meter (ATI Orion, Model 370, Anachemia, St. Pierre, QC, Canada) comprising a standard electrode (Orion, 9272BN). Standardisation of the electrodes was performed using buffer solutions at 4.0, 7.0 and 10.0 prior to measurement. Measurements were performed in duplicate.

Electrical conductivity measurement

The schematic of the static ohmic heating cell is shown in Figure 3.1. It comprised of a cylindrical glass cylinder of 2.48 cm radius in which a sample volume was introduced between two titanium electrodes. The cross-sectional surface area of electrodes was 18.1 cm^2. The gap between the electrodes was 20.69 cm. Voltage and AC current were supplied and controlled by a power unit which included a variable transformer, an isolation transformer, a voltage transducer, a current transducer, power

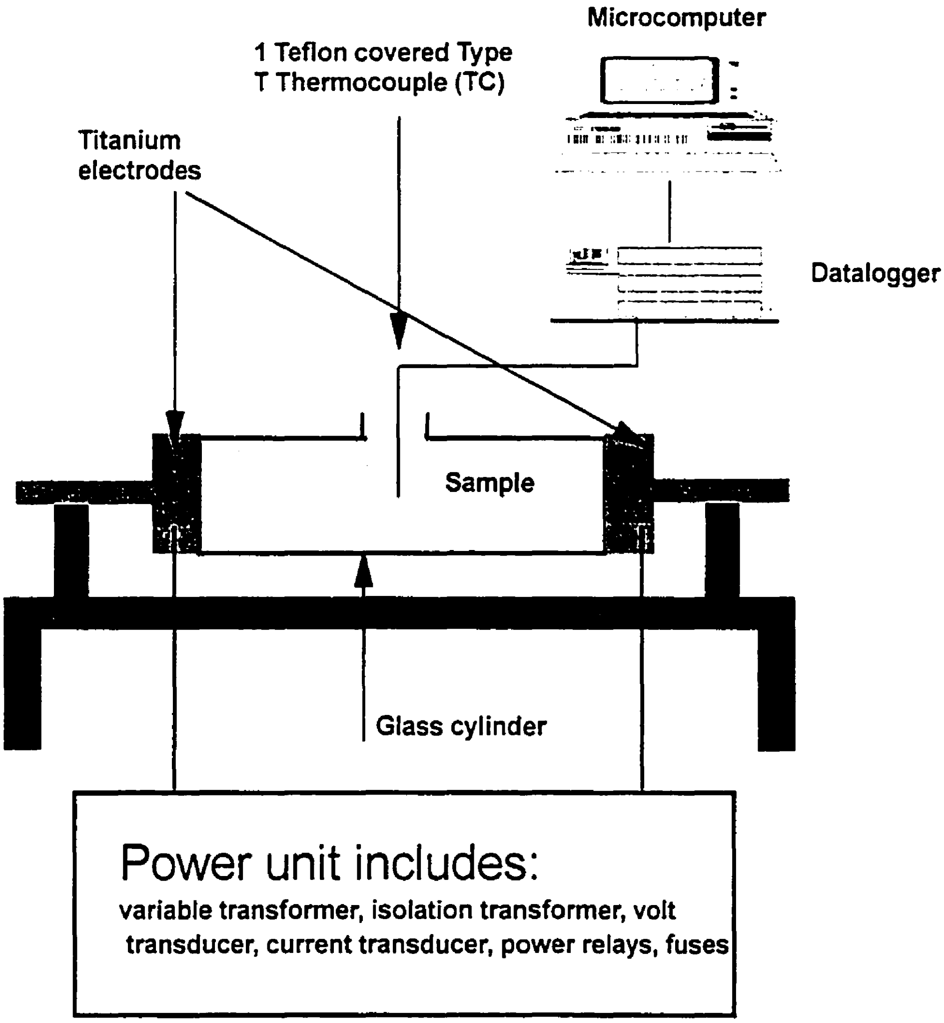


Figure 3.1 Schematic of the static ohmic heating cell

relays and fuses. One T-Type thermocouple, coated with Teflon to prevent interference with the electrical field, was fitted at the geometric centre of the cylinder. Thermal lags due to Teflon coating of the thermocouple were corrected using data from preliminary calibration experiments involving comparison with a certified mercury-in-glass thermometer and uncoated thermocouple junctions under conventional heating conditions. The thermocouple was checked for its accuracy against a certified mercury-in-glass thermometer (National Research Council NRC #1598, Canada) for a temperature range of 20 to 100 °C. As well, their response time was evaluated by immersing them from 20 to 100 °C in a temperature controlled silicone oil agitated bath. At the beginning of each experiment, a 400 ml of sample was introduced into the cylinder. The sample was heated from 20 to 100 °C using an alternating current of 60 Hz at a constant voltage of 150 V. During the experiment, time, temperature, voltage and current data were recorded at selected intervals on a datalogger (Fluke Hydra 2520, Fluke Corporation, Everett, WA) connected to a computer. A time limit of 10000 s of data recording was selected to stop the experiment if the sample did not reach 100 °C. For each experiment, values of voltage and current were used to calculate the electrical conductivity, which was plotted against temperature. All experiments were performed in duplicate.

Electrical conductivity calculation

Electrical conductivity (σ) of the samples was calculated using the following equation (Palaniappan and Sastry, 1991b):

$$\sigma = \left(\frac{1}{R}\right)\left(\frac{L}{A}\right)x100 \qquad [3.1]$$

Where L was the gap between the electrodes (cm) and A was the cross-sectional surface area of the electrodes (cm^2). R, the resistance of the sample in ohms was determined from voltage (V) and current (I) data:

$$R = \frac{V}{I} \qquad [3.2]$$

Design of experiment and statistical analysis

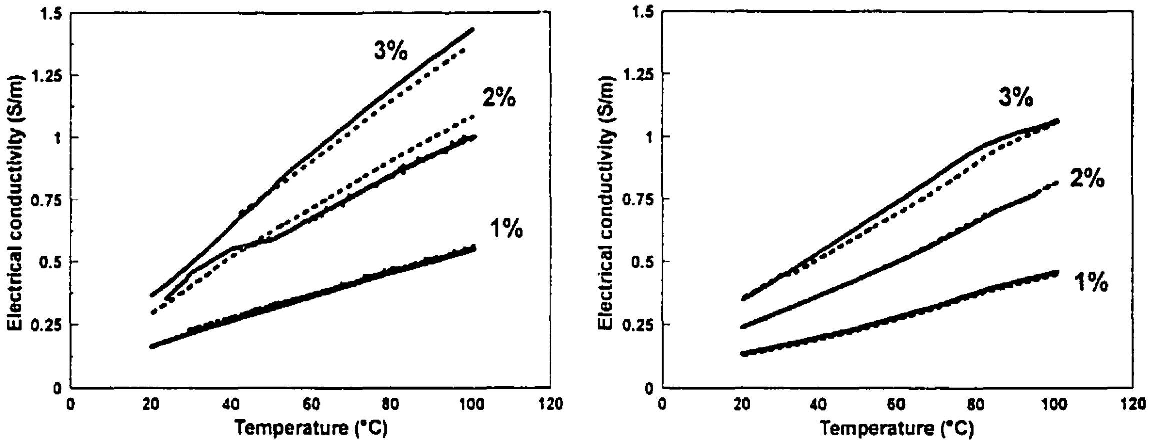
Regression analyses were performed on electrical conductivity data as a function of temperature and concentration with the Statistical Analysis System (SAS) using three procedures (REG, GLM and RSREG). The selection of the appropriate model for each type of hydrocolloid was based on the minimum number of meaningful parameters giving the best r-squares.

An analysis of variance was also conducted on electrical conductivities at the reference temperature (25 °C) and on the temperature constant (K_T) using a Generalised Linear Model (GLM) for the 5 types of hydrocolloids at a comparable concentration (3-4 %). A Duncan Multiple Range test was used for the comparison of the means.

RESULTS AND DISCUSSION

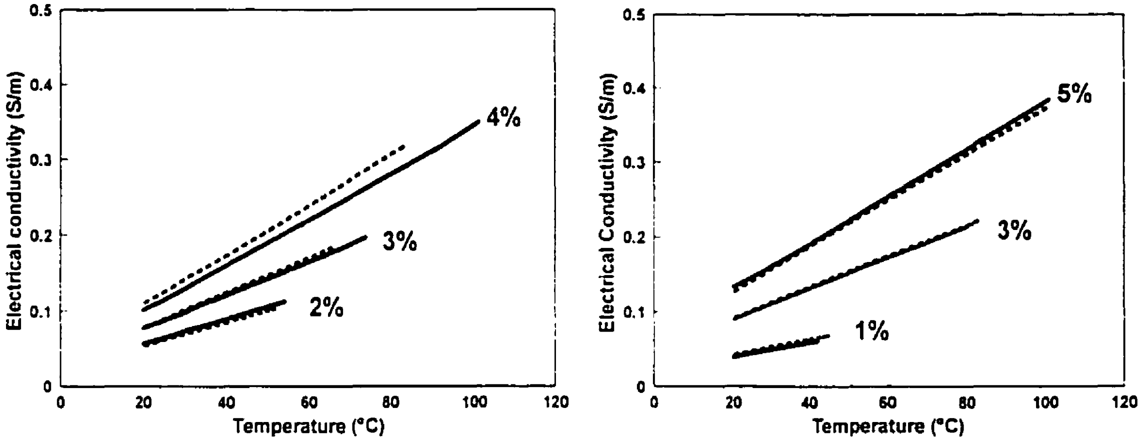
Electrical conductivity as affected by temperature

Figure 3.2 shows electrical conductivity values as influenced by concentration and temperature for all types of hydrocolloid solutions. The two lines for each experimental condition represent the replicates. A wide range of electrical conductivities were obtained: 1) 0.2 S/m at 25 °C and 1 % to 1.4 S/m at 100 °C and 3 % for carrageenan; 2) from 0.14 S/m at 25 °C and 1% to 1.1 S/m at 100 °C and 3 % for xanthan; 3) from 0.06 S/m at 25 °C to 0.37 S/m at 100 °C for pectin and gelatin samples and 4) from 0.05 S/m at 25 °C and 4 % to 0.21 S/m at 100 °C and 6 % for starch samples (linearly extrapolated value since the temperature never reached more than 55 °C before the 10000 s selected time limit for recording). The general trend was that the magnitude of σ increased with temperature and concentration. Electrical conductivities were observed to increase linearly with temperature in all cases.



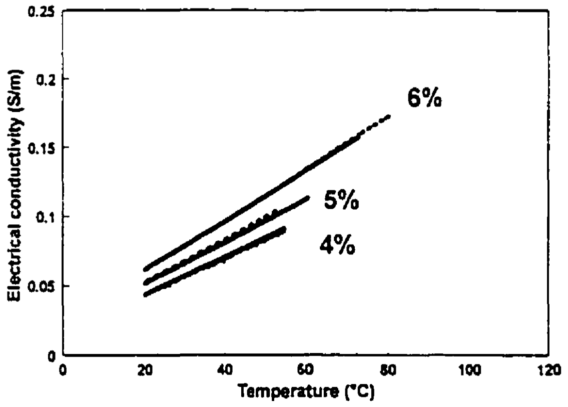
(a) carrageenan

(b) xanthan



(c) gelatin

(d) pectin



(e) starch

Figure 3.2 Temperature and concentration effects on electrical conductivities of hydrocolloid solutions

Experimental values of hydrocolloid solutions compared well with those reported for low viscosity liquids. Typical values between 0.50-1.2 S/m and 0.7-1.6 S/m, over a temperature of 20-80 °C, were measured by Palaniappan and Sastry (1991b) for low viscosity liquids (e.g. orange and tomato juice) respectively. In comparison, the electrical conductivity of a typical solid food is usually less than 0.5 S/m. However, if solid particles are soaked in salt solutions or salt is added as in a meat formulation for example (Palaniappan and Sastry, 1991a; Halden *et al.*, 1990), values of electrical conductivities will generally be higher than 0.5 S/m. Values of electrical conductivities for pectin, gelatin and starch samples were found to be as low as for some solid food particles. Few data have been reported for viscous liquids. Kim *et al.* (1996a) measured the electrical conductivity of a sauce of 5.5 % starch with 0.55 % salt as being 1.3 S/m. This is considerably greater than the electrical conductivity of a starch solution without added salt. They also reported electrical conductivities of 5.5 % starch solutions with two other levels of salt content (0.2 % and 2 %) as being 0.34 and 4.3 S/m respectively. Because of the salt addition to the starch solution, it was not possible to compare our experimental results to those results published by Kim *et al.* (1996a).

The electrical conductivity of samples was empirically modelled as a function of temperature using σ at 25 °C as a reference conductivity (σ_{25}) for each type and concentration of hydrocolloid solutions. The linear equation was expressed as:

$$\sigma_T = \sigma_{25} + K_T(T - 25) \qquad [3.3]$$

where T is in °C and T and σ_{25} are in S/m. K_T is in S/m°C. Fryer *et al.* (1993) expressed a linear relationship for high viscosity solution differently as:

$$\sigma = \sigma_0 + K_T(T) \qquad [3.4]$$

which anchors the value of σ_0 at 0 °C. But, results of reference electrical conductivity are usually not reported at 0 °C. According to Palaniappan and Sastry (1991b), the linear relationship for fruit juices could be expressed as:

$$\sigma = \sigma_{25}\left(1 + K_{TS}\left(T - 25\right)\right) \qquad [3.5]$$

The preferred equation form (i.e. equation [3.3]) was a combination of both i.e. anchoring the reference value of σ at 25 °C. Results of regression equations mainly σ_{25} and K_T for each type and concentration of hydrocolloid in solutions are listed in Table 3.1 along with coefficients of determination. Each value represents an average of two replicates and is included with the standard deviation obtained from the two replicates for a specified experimental condition. In all cases, r^2 were greater than 0.99 indicating the suitability of a linear model for changes in σ with respect to temperature for all types of hydrocolloid solutions.

The fact that a clear linear effect of temperature on electrical conductivities was observed is not surprising since it has also been reported by several authors (Palaniappan and Sastry, 1991ab; Fryer *et al.*, 1993; Yongsawatdigul *et al.*, 1995b) within a temperature range of 20-100 °C. This has a practical significance on the ohmic heating behaviour making it more efficient at higher temperatures. Fryer *et al.* (1993) demonstrated that if a series of solutions of carboxymethylcellulose (CMC) of similar initial electrical conductivity (0.95 S/m) at 20 °C but differing in viscosity (0.018, 0.064 and 0.8 Pa.s) are heated in a static ohmic heater, a linear temperature dependence is obtained with almost identical temperature coefficients (K_T) equal to 0.025 S/m °C. Smaller values were obtained for the hydrocolloid types used in this study. K_T was found to increase with concentration but it never reached more than 0.013 S/m °C (carrageenan at 3 %) (Table 3.1). However, this might be due to the fact that the electrical conductivity at 20 °C was never 0.9 S/m. Palaniappan and Sastry (1991b) have also published values of temperature constants (K_{TS}) for orange (0.0242 /°C) and tomato juices (0.0174 /°C) with values of σ_{25} being 0.863 S/m (tomato) and 0.567 S/m (orange). These values would be equivalent to 0.015 S/m°C (tomato juice) and 0.014 S/m°C (orange juice) [Sastry's K_{TS} is multiplied by σ_{25} in our equation]. These values were thus found to be comparable. Sastry and Palaniappan (1992c) measured the electrical conductivity and a temperature coefficient for sodium phosphate (0.025, 0.05, 0.1 M) as equivalent to 0.0051 S/m°C, 0.0079 S/m °C and 0.0142 S/m °C respectively, again values were similar to this study.

Table 3.1 **Parameters of the electrical conductivity model as a function of temperature**

Types	Concentration (%)	σ_{25} (S/m)	K_T (S/m °C)	r^2
Carrageenan	1	0.206 ± 0.005	0.00465 ± 0.00007	0.9983
	2	0.39 ± 0.03	0.009 ± 0.001	0.9963
	3	0.47 ± 0.04	0.013 ± 0.001	0.9983
Xanthan	1	0.1394 ± 0.0008	0.00410 ± 0.00008	0.9972
	2	0.25 ± 0.01	0.00710 ± 0.0003	0.9933
	3	0.4 ± 0.2	0.0090 ± 0.0001	0.9961
Gelatin	2	0.062 ± 0.002	0.00160 ± 0.00007	0.9990
	3	0.089 ± 0.002	0.0024 ± 0.0002	0.9991
	4	0.11 ± 0.01	0.0031 ± 0.0001	0.9988
Pectin	1	0.047 ± 0.002	0.0010 ± 0.0001	0.9934
	3	0.1011 ± 0.0006	0.00208 ± 0.00006	0.9960
	5	0.14 ± 0.01	0.0030 ± 0.0002	0.9996
Starch	4	0.051 ± 0.003	0.00128 ± 0.00006	0.9982
	5	0.057 ± 0.002	0.00148 ± 0.00005	0.9987
	6	0.069 ± 0.002	0.00184 ± 0.00004	0.9994

K_T is the temperature parameter term from equation [3.3]

Khalaf and Sastry (1996) have measured values of electrical conductivity for CMC solutions (low viscosity: $m = 0.179$ Pa.s^n, $n=0.72$ and medium viscosity: $m=0.87$ Pa.s^n, $n = 0.6$) in which salt was added. Values for temperature constants were equivalent to 0.0217 S/m°C and 0.037 S/m°C, again higher than in our equation. In these experiments, hydrocolloid solutions exhibited temperature constants that were similar to low viscosity juices in which no adjustment for electrical conductivity was performed.

For static heater situations, experiments revealed that the use of viscous carriers enhances ohmic heating as compared to the use of low viscosity fluids (de Alwis *et al.*, 1989). The effect was found to be similar to what was observed with particles. Although high viscosity carriers have lower electrical conductivity than low viscosity fluids, the rate of increase of this property as a function of temperature was found to be sharper for particles (Sastry and Palaniappan, 1992c). This temperature enhancement is believed to be the principal reason that heating is enhanced for high viscosity fluids as well as for particles.

Electrical conductivity as affected by concentration

For each type of hydrocolloid solution, σ_{25} and K_T were plotted against concentration (results not shown). Both parameters i.e. σ_{25} and K_T were found to increase linearly with increasing concentrations for all hydrocolloid solutions. For carrageenan, xanthan, gelatin and pectin, the σ_{25} values nearly doubled, while for starch solutions electrical conductivities at 25 °C and temperature constants were relatively unaffected by concentration and temperature. A linear relationship was fitted for $\sigma_{c,25}$ as a function of concentration forcing the intercept through 0 with r^2 greater than 0.89:

$$\sigma_{C,25} = K_{C,25} C \qquad [3.6]$$

Values of $K_{C,25}$ (S/m%) were obtained as 0.17 (1-3 %), 0.133 (1-3 %), 0.0299 (3-5 %), 0.0305 (1-5 %), 0.013 (4-6 %) for carrageenan, xanthan, gelatin, pectin and starch within their respective range of concentrations.

The observed positive effect of hydrocolloid concentration on electrical conductivity contradicts what was reported for fruit juices (Palaniappan and Sastry, 1991b). A negative effect of solids concentration on electrical conductivities of both orange and tomato juice was observed by Palaniappan and Sastry (1991b), which is to be expected from values of electrical conductivity of solids and liquids. Palaniappan and Sastry (1991b) also reported a slight decrease in electrical conductivity with increasing particle size in carrot juice at a temperature range of 20-100 °C. However, Sastry and Palaniappan (1992c) demonstrated that the electrical conductivity of sodium phosphate solutions of various concentrations increased as the concentration increased in the solution.

The positive effect of hydrocolloid concentration on electrical conductivity might have been related in part to the chemical composition of these hydrocolloids. Carrageenans are linear chains of polysaccharides. There is the iota, kappa and lambda carrageenan. Kappa carrageenan forms a gel on cooling in the presence of potassium ions or proteins while iota carrageenan requires the presence of calcium ions to form a gel and lambda carrageenan is incapable of forming a gel. Carrageenan is an acidic gum, that is always associated with counter ions. Xanthan gum, a high molecular weight heteropolysaccharide, contains various substituents on its backbone linear chain that is identical to cellulose. The presence of glucuronic acid units or carboxyl groups on these side chains renders the gum molecule anionic. It can be neutralised by cations such as Na+, K+ and Ca++. Both carrageenan and xanthan are charged molecules in solutions and this could explain their better efficiency upon ohmic heating when compared with gelatin, pectin and starch. Starch is composed of glucose units, which can be either linear through a carbon α 1-4 to form amylose, or the linear chain can be branched to form amylopectin. Starch is a neutral gum and this could explain its poor behaviour upon ohmic heating. Gelatin is produced from collagen. It is a mixture of protein molecules of similar structure. Building blocks of gelatin are different from those for polysaccharides. Gelation involves hydrogen bonding between amino acid residues forming pockets in which water molecule is trapped. Pectins are polymeric carbohydrates composed of a chain of galacturonic acid units. The galacturonic acid chain is partially esterified as methyl esters. The degree of esterification (DE) indicates the percentage of galacturonic acid units in the methyl ester form and it determines the functional properties of pectin. Although the building blocks or pectin and gelatin are different, the electrical conductivity values were found to be similar upon ohmic heating conditions at all concentrations. Consequently, this phenomenon cannot be totally explained by the composition of hydrocolloids.

To further explain the major differences observed on electrical conductivity with hydrocolloid types, ash content of dried hydrocolloid powders as well as pH were determined to identify the presence of other ionic constituents which might also have an influence on the ohmic heating behaviour of these hydrocolloid solutions. Palaniappan and Sastry (1991b) pointed out that the nature of ions and the ionic movement of the liquid mainly affect electrical conductivity data. The level of pH varied from 3.2 for pectin solutions to 8.2-9.1 for carrageenan solutions. Gelatin (5.6-5.8), xanthan (5.8-6.0) and starch (5.7-6.6) had intermediate pH values. There was no definite effect of concentration on pH values. It was found that pH did not follow the same trend as electrical conductivity. The ash content of the dried hydrocolloid powder was determined on a dry basis. The moisture content of all hydrocolloid powders were 10 % except for carrageenan, which had a moisture content of 6 %. Ash content of dried hydrocolloids was found to follow the same trend as electrical conductivity values. Carrageenan, exhibited the highest ash content (21 %) and was observed to be the most efficient hydrocolloid for ohmic heating. It was followed by xanthan (8.7 %). Pectin and gelatin were found to have a similar amount of ash (1.2 %) which could explain their similarity in electrical conductivity values. Finally, the ash content of starch was 0.6, the lowest amount explaining its poor performance for ohmic heating. The following linear regression was obtained for the relationship between σ_{25} and the ash content:

$$\sigma_{25} = 0.0982 + 0.2876 \log(\%ash) \qquad r = 0.9913 \qquad [3.7]$$

As well, a similar equation was obtained for K_T and the ash content:

$$K_T = 0.0023 + 0.0074 \log(\%ash) \qquad r^2 = 0.9851 \qquad [3.8]$$

Combined effect of temperature and concentration on electrical conductivities

In performing the regression analysis for each hydrocolloid, a modified dependent variable for electrical conductivity ($\sigma - \sigma_{c,25}$) and a modified independent variable for temperature (T-25) were selected to anchor reference values of electrical conductivity at a reference temperature of 25 °C in order to allow for the comparison with available published data. The independent variable concentration (C) was expressed in %. A first regression model, using the REG procedure, was used to relate electrical conductivity ($\sigma - \sigma_{c,25}$) to the temperature (T-25) and concentration (C) effects without any intercept. It is worth noticing that REG allows only for the computation of main effects without considering any interaction term. R-squares were less than 0.90 for all hydrocolloid types indicating that the main effects were not the only ones important. Next, a complete response surface model (RSREG) was utilised to obtain a regression equation for each type of hydrocolloid. It revealed that only linear and cross products were significant with r^2 over 0.99 therefore eliminating the quadratic effect of both parameters. Finally, the results of the analysis of variance for the final regression model were generated using the GLM procedure, controlling the number of parameters. It contained only two main effects (T-25, C), an interaction term (T-25)*C without any intercept. The temperature term, (T-25) and the interaction term, (T-25)*C, were found to be highly significant ($p<0.001$) in establishing the relationship between ($\sigma - \sigma_{c,25}$) and (T-25) and C. It has to be pointed out that values of the temperature constant parameter (K_T) and the interaction term parameter (K_{TC}) were similar to the ones obtained using RSREG. The resulting regression equation is proposed as:

$$\sigma = \sigma_{C,25} + K_T(T-25) + K_{TC}(T-25)(C) \qquad [3.9]$$

Values for each parameter of regression equations for each hydrocolloid type are listed in Table 3.2 along with r-squares. The effect of concentration on electrical conductivity and the combined effect of temperature and concentration were higher for carrageenan, followed by xanthan, gelatin, pectin and starch. However, the highest temperature effect was observed for xanthan followed by carrageenan, pectin,

Table 3.2 **Parameters for the electrical conductivity model as a function of temperature and concentration of the solution**

Types	$K_{C,25}$ (S/m %)	K_T (S/m°C)	K_{TC} (S/m % °C)	r^2
Carrageenan	0.17	8.65E-04	3.90E-03	0.9953
Xanthan	0.133	1.78E-03	2.46E-03	0.9990
Gelatin	0.0299	5.29E-05	7.67E-04	0.9980
Pectin	0.0305	5.76E-04	4.81E-04	0.9955
Starch	0.013	1.95E-04	2.71E-04	0.9985

$K_{C,25}$ is the concentration parameter term at 25°C from equation [3.6]

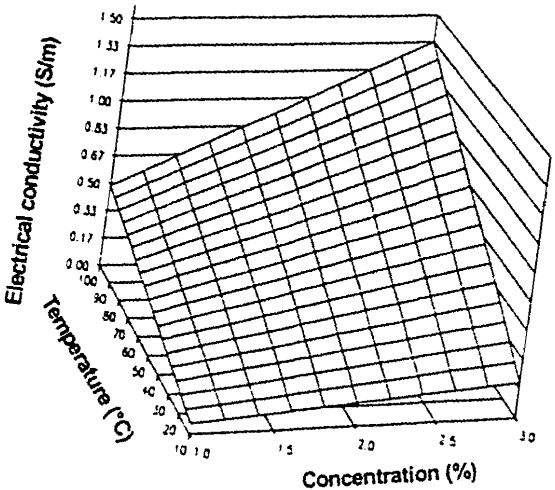
K_T is the temperature parameter term from equation [3.9]

K_{TC} is the interaction parameter term between (T-25) and C from equation [3.9] starch and finally, gelatin. It has to be pointed that the temperature constants obtained from the combined equation were lower that the temperature constant of equation [3.3]. This is related to the fact that a combined temperature*concentration term is included in equation [3.9].

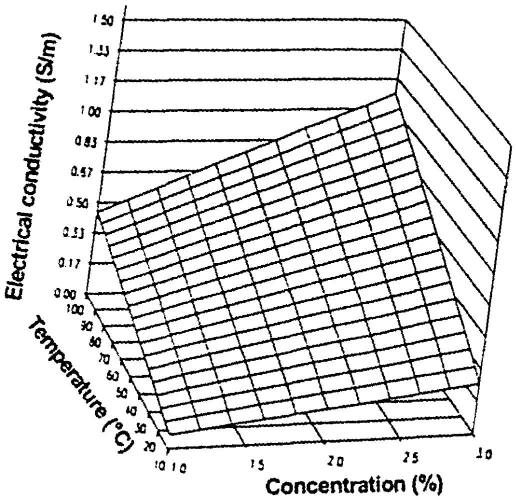
Parameters of equation [3.9] included in Table 3.2 were used to generate response surface plots showing σ as influenced by temperature and concentration and are presented in Figure 3.3 for each hydrocolloid solutions. The plots show clearly that σ increased with temperature and concentration. As the concentration is increased, the effect of temperature becomes more important. Plots also demonstrated that the magnitude of σ is largely affected by hydrocolloid type.

Comparison of electrical conductivity at a comparable concentration

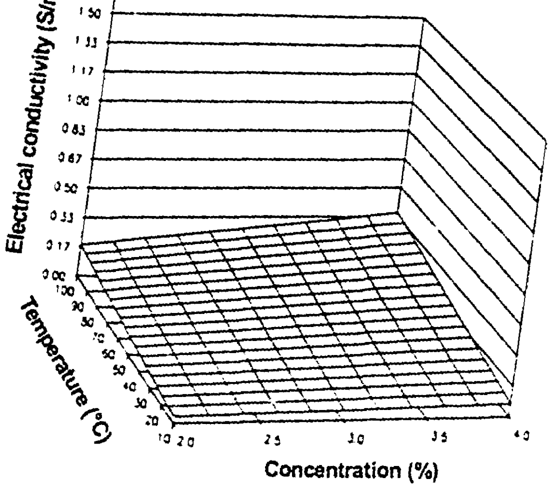
A comparison of the electrical conductivity profiles as a function of temperature is shown in Figure 3.4 for all types of hydrocolloid solutions at a comparable concentration (3-4 %). It has to be pointed out that carrageenan, xanthan and gelatin solutions at 3 % were gels at room temperature whereas starch and pectin mixtures were viscous solutions. At any given temperature, the electrical conductivities of carrageenan solutions were higher than for xanthan. Gelatin and pectin solutions exhibited similar but lower electrical conductivities. Starch solutions were found to have the lowest electrical conductivities. The type of hydrocolloid significantly affected σ_{25} and K_T at a level of 5 %. A comparison of means using the Duncan Multiple Range test showed that except for gelatin and pectin, means σ_{25} and K_T were found to be significantly different at a 3 % concentration (results not shown).



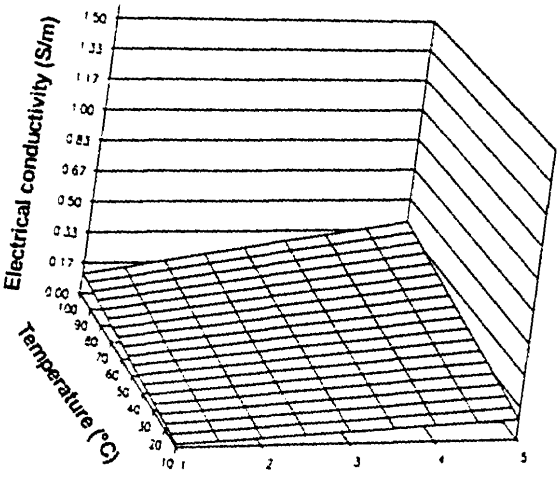
(a) carrageenan



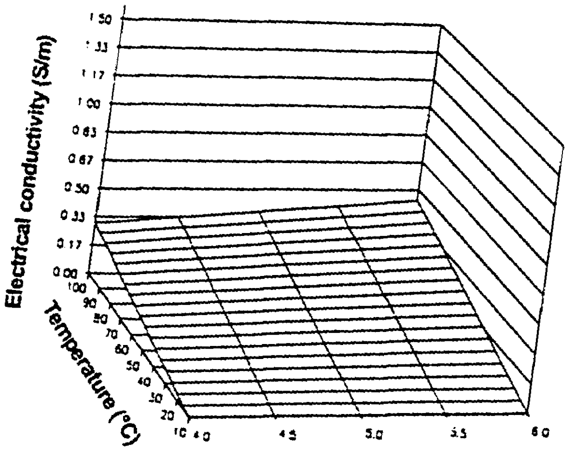
(b) xanthan



(c) gelatin



(d) pectin



(e) starch

Figure 3.3 Response surface plots for all types of hydrocolloids

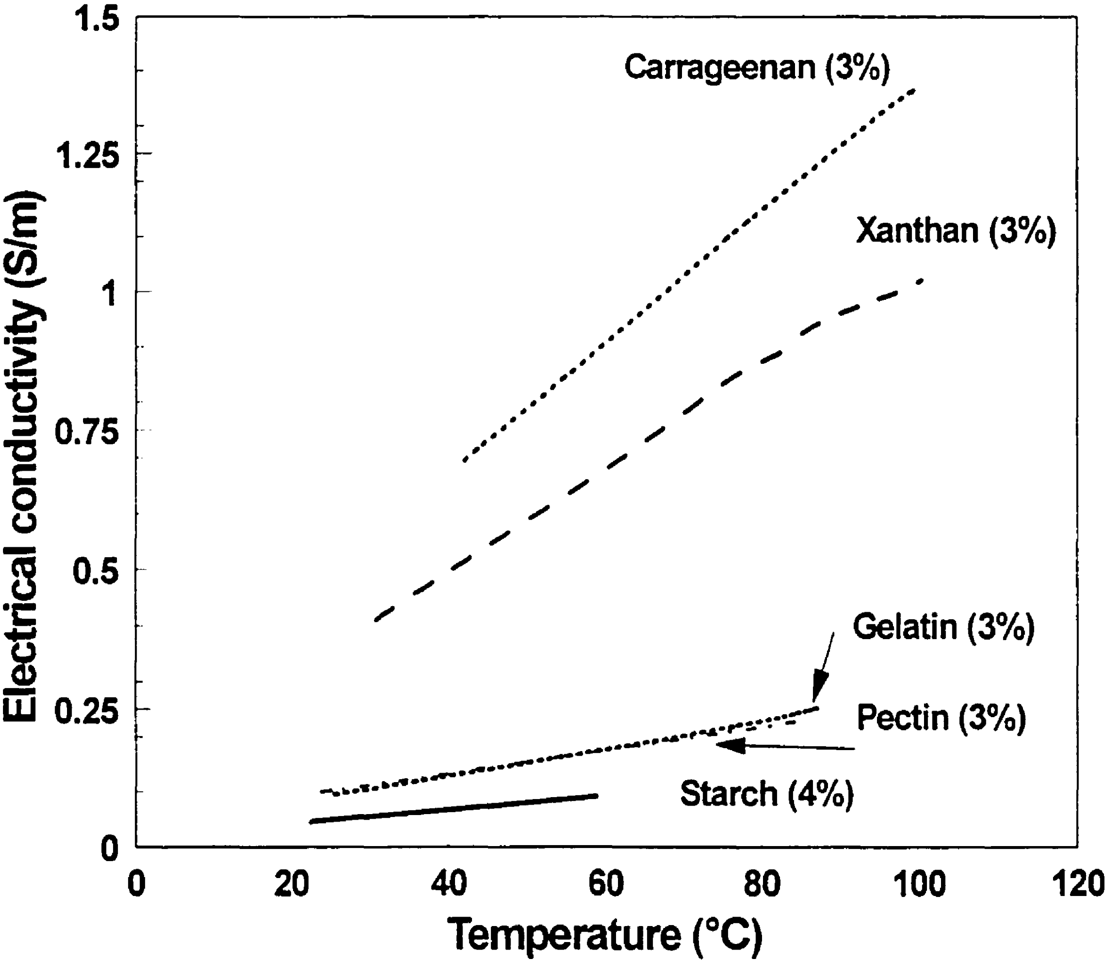


Figure 3.4 Comparison of electrical conductivity for hydrocolloid solutions

CONCLUSIONS

Results from this study give some insight into the electrical conductivity of hydrocolloid solutions as influenced by temperature and concentration. As expected, electrical conductivity increased linearly with temperature. Electrical conductivity also increased with concentration. Regression equations were established for electrical conductivity as a function of temperature and concentration. Major differences were observed between hydrocolloids that were mainly attributed to the ash content of hydrocolloids.

The behaviour of food hydrocolloids in solutions upon ohmic heating is virtually unknown and probably quite different than in conventional heating. Data on electrical conductivities for these products alone and in combination with other compounds which covers a variety of foods are needed for the most appropriate selection and for the appropriate design of the ohmic heating process. In this work, some data were obtained which clearly indicated major differences between hydrocolloid types upon ohmic heating.

CHAPTER 4

OHMIC HEATING BEHAVIOUR OF HYDROCOLLOID SOLUTIONS

CONNECTING STATEMENT

In chapter 3, the electrical conductivities were measured for selected hydrocolloids in aqueous solutions at various concentrations. Major differences were observed between hydrocolloid types. These were attributed to the hydrocolloids structure and their associated ash content.

The objective of this chapter was to determine time/temperature profiles and to evaluate the uniformity of heating of these selected hydrocolloids in solution at various concentrations during ohmic heating in a static cell in order to have a more comprehensive understanding of their suitability for ohmic heating.

This following manuscript has been published based on material presented in this chapter: Ohmic heating behaviour of hydrocolloid solutions. 1998. *Food Res. Intl.* **31(6-7):** 493-502. The authors are: Michèle Marcotte (Ph.D. Candidate, who planned and conducted experiments, analysed results and wrote the manuscript), Hosahalli Ramaswamy (thesis supervisor, who guided the student, corrected, edited and reviewed the manuscript), Gabriel Piette (who corrected and reviewed the manuscript).

ABSTRACT

Aqueous solutions of 5 hydrocolloids (carrageenan, 1-3 %; xanthan, 1-3 %; pectin, 1-5 %; gelatin, 2-4 % and starch, 4-6 %) were heated in a static ohmic heating cell using a voltage gradient of 7.24 V/cm. Time and temperature data, recorded at selected time intervals, were used to study the effect of concentration and temperature on the ohmic heating behaviour of hydrocolloid solutions. Of the test samples examined, carrageenan gave the shortest time to raise the temperature from 20 to 100 °C : 4200, 1600 and 1100 s at 1, 2 and 3 % concentration, respectively. For the same temperature rise, xanthan samples required 5500, 2300 and 1400 s at 1, 2 and 3 % concentration levels. Pectin and gelatin samples were found to exhibit even lower, but similar heating profiles. At the highest concentration (5 %), pectin took 7300 s to reach 100 °C from 20 °C, and at all other concentrations, the time limit of 10000 s was exceeded before it reached 100 °C. The temperature of starch solutions never exceeded 62 °C within the specified time limit. Heating was found to be uniform throughout samples of carrageenan, pectin (1-3 %) and gelatin. For xanthan and starch solutions, some non-uniformity in temperature profiles was observed. The observed ohmic heating behaviour of hydrocolloid solutions corresponded well with their electrical conductivity values. The homogeneity of heating was related to the rheological properties of hydrocolloid solutions and their behaviour at high temperatures.

INTRODUCTION

Currently, liquid foods with or without added hydrocolloids such as starch, carrageenan etc. are thermally processed using conventional plate and frame, tubular or scraped surface heat exchangers (Parrot, 1992) under continuous flow conditions. Aseptic processing of homogeneous low-acid products has been a commercial reality in the United States for 40 years with a rapid expansion since the approval by the Food and Drug Administration (FDA) of the use of hydrogen peroxide as a sterilant for packaging material in February 1981. The conventional approach for thermal design of homogeneous liquids in a continuous process is to calculate the lethality that accumulates in the holding tube only.

Dignan *et al.* (1989) published a paper on the requirements of the FDA to establish a process for continuous heat-hold-cool sterilisation of low-acid liquids containing particulates. Although the procedure is tedious and time consuming, FDA approved for the first time in May 1997 a conventional aseptic process for potato soups (Palaniappan and Sizer, 1997).

As an alternative solution to conventional aseptic processing, a continuous ohmic heating technology for liquids containing particulates was developed by APV in the 1980's (Skudder, 1988; Skudder and Biss, 1987). Since then, commercial plants have been installed around the world. This technological breakthrough was recognised at the 1996 Institute of Food Technologists (IFT) Annual Meeting (Giese, 1996). One of the advantages of ohmic heating is that particles can heat faster than the liquid under certain conditions (de Alwis *et al.*, 1989; Halden *et al.*, 1990; Sastry, 1992a), i.e. if overall electrical conductivities of liquid and solid particles are properly matched, it reduces the thermal design as for homogeneous liquid foods.

A vast amount of data has been published on ohmic heating of heterogeneous solid foods mainly in static heaters, but ohmic heating of liquids has not attracted much attention (Fryer *et al.*, 1993). Ohmic heating characteristics have been reported for some low viscosity juices (Palaniappan and Sastry, 1991b), but ohmic heating data on high viscosity fluids are scarce. Only recently, Fryer *et al.* (1993) and Khalaf and Sastry (1996) emphasised the importance of the liquid phase in ohmic heating of fluids containing particulates.

In order to understand the thermal behaviour of the liquid phase in heterogeneous systems, Fryer *et al.* (1993) used two simple limiting cases of an infinite linear field around a two-dimensional electrically insulating cylinder (wooden cylinder of 38mm diameter) representing in one case no heat conduction and a constant electrical conductivity of the liquid and in the second case an infinite thermal conductivity i.e. representing a conduction and convective heat transfer infinitely rapid. Analytical solutions for liquid temperatures were compared to experimental data generated in a static ohmic heater on salt solutions of various concentration (low viscosity) and CMC fluids (high viscosity). The initial rate of change of liquid temperature with time was well predicted as compared to experiments for the hypothesis of no heat conduction. However, liquid temperature was poorly predicted. Theory and experiments were reported to compare well for low viscosity solutions if an infinite thermal conductivity was assumed. It was concluded that the bulk fluid was well-mixed for low viscosity solutions in a static ohmic heater. At high temperature, the model overpredicted the liquid temperature.

Sastry and Palaniappan (1992c) developed a model for the prediction of temperatures of mixtures of low viscosity liquids and multiple particles in a static ohmic heater. They assumed that a fluid of low viscosity, permitting rapid mixing, will experience small temperature gradients. Heat losses from the liquid through the walls were also considered. Experimentally, ohmic heating profiles of potato cubes in sodium phosphate solutions of various concentrations (0.025, 0.05 and 0.1 M) were gathered and used to validate the model. Samples with higher sodium phosphate concentration, having higher electrical conductivities, were reported to heat more rapidly than the particles. Interesting observations were found about the relative heating rates of liquid and particles. At low concentrations of sodium phosphate, the particle centre heated faster than the fluid whereas at higher concentrations, the temperature of the particle lagged the liquid. The difference was attributed to the temperature coefficient of σ being higher for the particles than for the liquid even though σ is smaller at room temperature for solid particles.

More recently, Khalaf and Sastry (1996) compared three ohmic heating systems: a static cell, a vibrating unit and a continuous system. Fluids having the same electrical conductivity but different viscosities and the same amount of particles were used. Using static ohmic heating conditions, it was found that heating rates of the fluid and particles were not significantly affected by fluid viscosities. However, with sufficient agitation, the rate of heating increased with fluid viscosity. Enhanced heating of the fluid phase resulted in an increased temperature difference between the fluid and solids, which counteracted the effect of low heat transfer coefficient.

The advantages of using ohmic heating for fluids containing particulates have thus been demonstrated in the literature, but no detailed study has been made on the heating behaviour of hydrocolloid solutions, especially at the concentration levels used commercially. Hydrocolloids are used as homogeneous thick liquids in a variety of food products such as puddings, sauces, etc. They are also used as carrier fluids while processing particulate foods (Kim *et al.*, 1996a). The objective of this work was to evaluate the ohmic heating behaviour of selected hydrocolloid solutions.

MATERIALS AND METHODS

Hydrocolloid solution preparation

Five commercial hydrocolloids were obtained: xanthan (Rhodigel, lot # 9635001, Rhone-Poulenc Food Ingredients, Washington, PA, USA), carrageenan (Grinsted Carrageenan, CL210, Danisco Ingredients Canada, Rexdale, ON, Canada), pectin (Grinsted Pectin, RS400 lot # 701J547, Danisco Ingredients Canada, Rexdale, ON, Canada), gelatin (Gelatin, type B 250 bloom, Germantown Canada Inc., Scarborough, ON, Canada), starch (Thermo-flo starch, NFPA 0934 lot # LF5919, National Starch and Chemical Corp., Bridgewater, NJ, USA). Three levels of concentration for each hydrocolloid were prepared in distilled water: xanthan (1, 2 and 3 %), carrageenan (1, 2 and 3 %), pectin (1, 3 and 5 %), gelatin (2, 3 and 4 %), starch (4, 5 and 6 %). Hydrocolloid powders were first solubilised in distilled water using a high-speed blender for 8 min at a high temperature (80 °C). Solutions were centrifuged (Centrifuge, Model GS-6, Palo Alto, CA, USA) at 896 g for 5 min to remove entrapped air bubbles and cooled. Each solution was prepared in duplicate. Levels of concentration for each hydrocolloid type were determined from preliminary experiments to obtain a range of viscosities.

Rheological Measurement

Rheological properties of hydrocolloid solutions were evaluated using a rotational viscometer (Rotovisco, Model RV20, Haake Mess-Technik, Karlsruhe, Germany) equipped with an M5 OSC measuring head and a MV2 rotor. Solution samples were loaded into the cylindrical cup and allowed to equilibrate at a setpoint temperature for 20 min in a water bath. Experiments were carried out in duplicates at four temperatures: 20, 40, 60 and 80 °C. A computer controlled program (Rheocontroller, RC20 module, Haake Mess-Technik, Karlsruhe, Germany) in a rotational mode was used to shear samples at a linear rate from 0 to 300 s^{-1} in 3 min. This was followed by a stress decay at a constant shear rate of 300 s^{-1} for 10 min and finally by a linearly decreasing shear from 300 s^{-1} to 0 during 3 min. Silicone oil standards (Cannon Instrument Company, State College, PA, USA) were used to verify the rheometer. Shear stress - shear rate data were gathered as rheograms. Apparent viscosities were calculated at 300 s^{-1} for each combination of hydrocolloid type, concentration and temperature as a ratio of the experimental shear stress over the constant shear rate of 300 s^{-1}. Other details on rheological behaviour have been reported elsewhere (Marcotte and Ramaswamy, 1997).

Experimental set-up

Figure 4.1a represents the schematic of the static ohmic heating cell. A cylindrical glass cylinder of 2.48 cm radius was used to hold a sample between two titanium electrodes having a cross-sectional surface area of 18.1 cm^2. The gap between the electrodes was 20.69 cm. Voltage and AC current were supplied and controlled by a power unit which comprised of a variable transformer, an isolation transformer, a voltage transducer, a current transducer, power relays and fuses. The electrical circuit schematic is presented in Figure 4.1b. Four T-type thermocouples, coated with Teflon to prevent interference with the electrical field were fitted in the cylindrical tube to monitor the temperature of test samples during the experiment. One thermocouple was placed close to the electrode (TE) and one was fitted at the geometric centre of the cylinder (TC). Two thermocouples were placed at mid-point between the centre of the cylinder and the electrode in each direction (T1 and T2). Additional details of the setup and thermocouple assembly have been previously discussed (Chapter 3). Thermal lags due to Teflon coating of thermocouples were corrected using data preliminary calibration experiments involving comparison with a certified mercury-in-glass thermometer (National Research Council, NRC # 1598, Canada) and uncoated thermocouple junctions under conventional

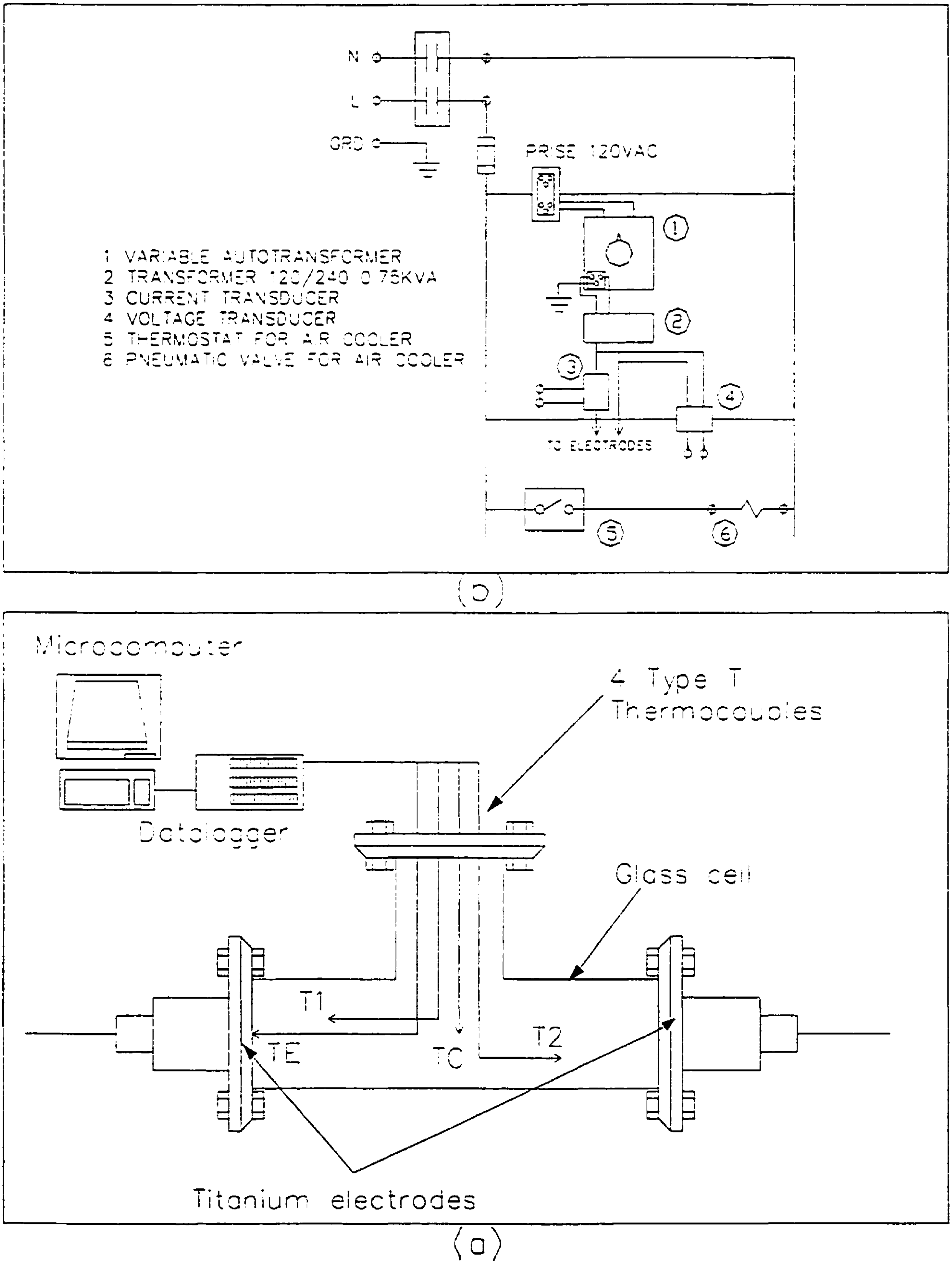


Figure 4.1 a) Schematic of the experimental static ohmic heating cell
b) Schematic of the electrical circuit

heating conditions. As well, their response time was evaluated by immersing them from 20-100 °C. De Alwis *et al.* (1989) noted that the use of thermocouples with ferromagnetic thermo-elements (e.g. alumel in type K) may give errors due to the interactions between the temperature gradient and the magnetic field experienced by the thermocouple.

Data gathering

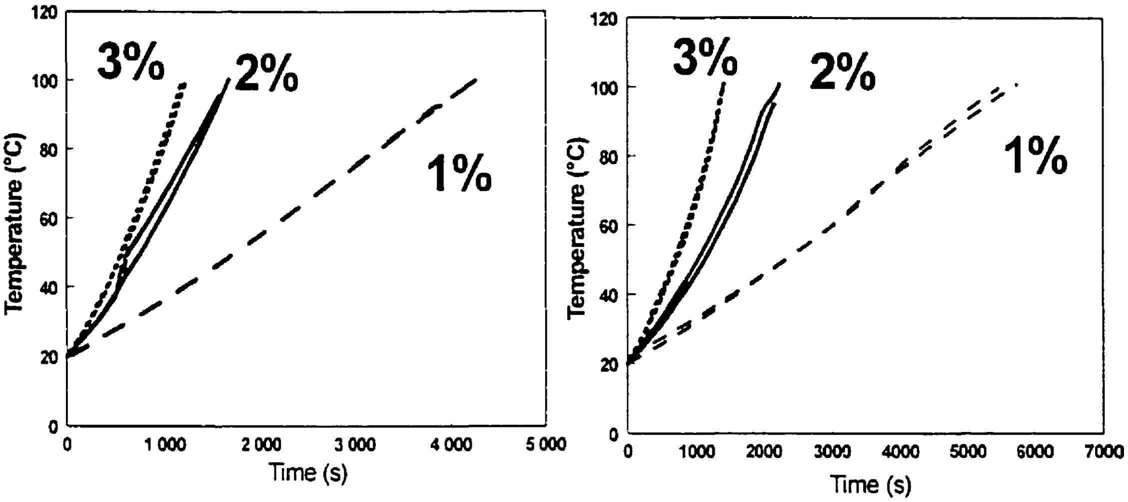
At the beginning of each experiment, 400 ml of sample was introduced into the cylinder. The sample was heated from 20 °C to 100 °C using an alternating current of 60 Hz at a constant voltage of 150 V with a constant voltage gradient of 7.24 V/cm. During the experiment, time, temperature, voltage and current data were recorded at selected time intervals on a datalogger (Model Hydra 2625A, John Fluke MFG Co. Inc., Everett, WA) connected to a computer. Values of voltage and current were used to calculate electrical conductivities using Palaniappan and Sastry (1991b)'s method. More details are given elsewhere (Chapter 3 and Marcotte and Ramaswamy, 1998). Time-temperature profiles were plotted and compared for hydrocolloid solutions. All experiments were performed in duplicates. A time limit of 10000 s of data recording was selected to stop the experiment if the sample did not reach 100 °C.

Experimental heating rates were obtained by calculating the slopes of the tangents to the curve of temperature against time, giving values of dT/dt directly at time intervals. First derivatives (dT/dt) at given t were computed using a spline FORTRAN 90 (Fortran Powerstation, Professional Edition, Version 4.0, Microsoft Corporation, Redmond, WA) subroutine program. Heating rates were only calculated for carrageenan and xanthan solution at 3 % concentration.

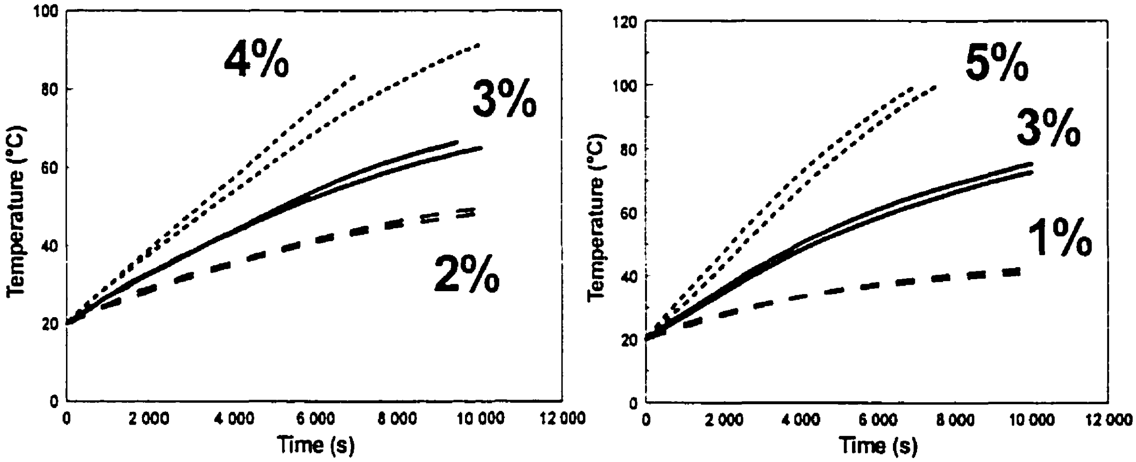
RESULTS AND DISCUSSION

Heating behaviour

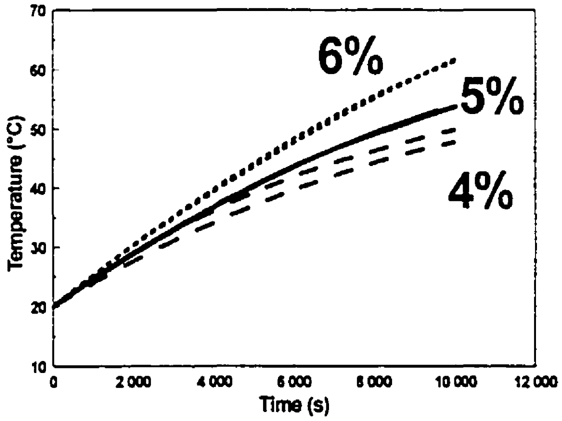
Typical heating curves for all hydrocolloid solutions are presented on Figure 4.2. The non-linear or exponential heating curve observed for carrageenan and xanthan is to



(a) carrageenan (b) xanthan



(c) gelatin (d) pectin



(e) starch

Figure 4.2 **Typical time-temperature profiles for carrageenan, xanthan, gelatin, pectin and starch at various concentrations**

be expected in a static ohmic heating system because the electrical conductivity (σ) increases substantially with temperature (Palaniappan and Sastry, 1991b).

The concave shape of the curve for pectin, gelatin and starch indicated that heat losses to the surroundings occurred during heating for all three hydrocolloids. For each hydrocolloid type, it is interesting to point out that as the concentration was increased the processing time to reach 100 °C from 20 °C was considerably reduced even though it can be a very viscous mixture. As a matter of fact, xanthan 3 % was a gel at room temperature whereas xanthan at 1 % was a thick solution.

Table 4.1 gives the processing time from 20 to 100 °C for each hydrocolloid solution. Of the thickening agents examined, carrageenan gave the shortest time to raise the temperature from 20 to 100 °C, 1100 s (18 min) at 3 % concentration, 1600 s (27 min) at 2 % and 4200 s (70 min) at 3 %. It was followed by xanthan samples with a time of 1400 s at 3 %, 2300 s at 2 % and 5500 s at 1 %. For pectin solution at 1-3 %, the temperature of 100 °C was never reached whereas it took 7300 s to reach 100 °C at 5 % concentration. Gelatin samples never reached 100 °C within the time limit fixed at 10000 s. But the end temperature increased as the concentration was increased. Pectin and gelatin samples were found to exhibit lower, but similar heating rates. Starch solutions never reached more than 62 °C within the selected time limit of 10000 s even at the highest concentration of 6 %.

Electrical conductivity vs. ohmic heating

Table 4.2 lists values of electrical conductivities at 25 and 100°C, the corresponding pH value of hydrocolloid solutions and the ash content of the dry hydrocolloid powders reported in details elsewhere (Chapter 3 and Marcotte and Ramaswamy, 1998). From the lowest to the highest concentration, σ values almost doubled or tripled for all hydrocolloids. Same trend was observed for σ between the two temperatures, 25 and 100 °C. Trends in electrical conductivity values were not found to be related to pH, but directly related to their ash content. This could explain the better heating behaviour of carrageenan solutions which had the highest ash content (21 %), followed by xanthan samples, found to have 8.7 % ash. Pectin and gelatin samples, with

Table 4.1 **Processing time from 20-100 °C during ohmic heating of all hydrocolloid types**

Type	Concentration (%)	Time (s)
Carrageenan	1	4200
	2	1600
	3	1100
Xanthan	1	5500
	2	2300
	3	1400
Gelatin	2	10000 (49 °C)
	3	10000 (66 °C)
	4	10000 (92 °C)
Pectin	1	10000 (41 °C)
	3	10000 (74 °C)
	5	7300
Starch	4	10000 (48 °C)
	5	10000 (53 °C)
	6	10000 (62 °C)

Table 4.2 **Values of electrical conductivities at various temperatures as well as the pH of the solutions and the ash content**

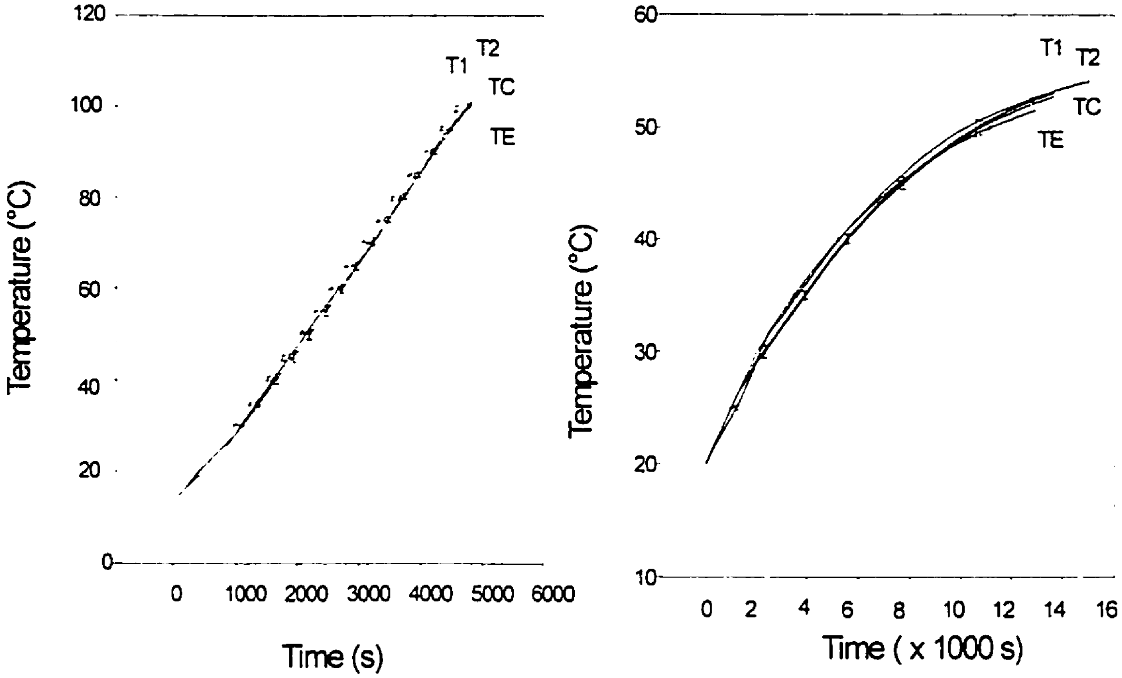
Types	Concentration (% w/w)	σ_{25} (S/m)	σ_{100} (S/m)	pH	Ash (%)
Carrageenan	1	0.206	0.553	8.5	20.8
	2	0.385	1.046	8.2	
	3	0.470	1.407	9.1	
Xanthan	1	0.139	0.446	5.8	8.7
	2	0.250	0.777	6.0	
	3	0.386	1.060	6.0	
Gelatin	2	0.062	0.183	5.6	1.2
	3	0.089	0.262	5.7	
	4	0.114	0.360	5.8	
Pectin	1	0.047	0.172	3.4	1.2
	3	0.101	0.259	3.3	
	5	0.137	0.376	3.2	
Starch	4	0.051	0.148	6.6	0.6
	5	0.057	0.168	6.3	
	6	0.069	0.214	5.7	

low but similar ash content (1.2 %) had similar electrical conductivities and expectedly similar heating behaviour. Starch solutions, having the lowest amount of ash (0.6 %), were found to have the lowest electrical conductivity values and the lowest ohmic heating rate. Thus, the ohmic heating efficiency followed the same trend as the electrical conductivity values. As electrical conductivity values increased, the heating time to reach a target temperature decreased.

Uniformity of heating

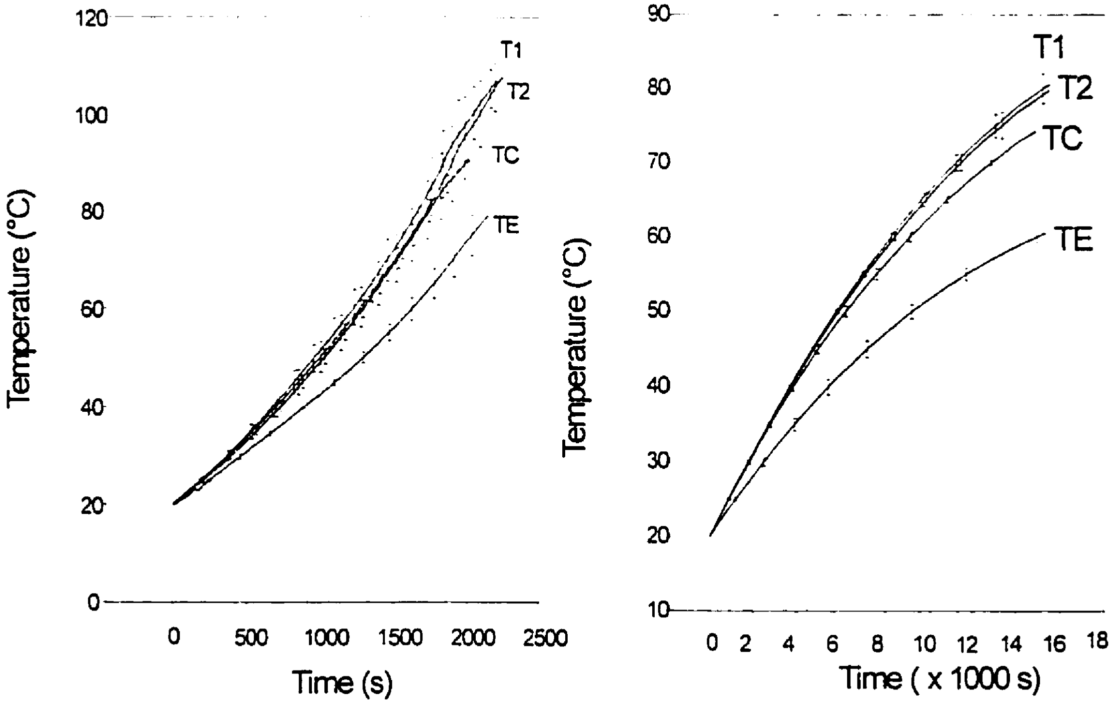
A typical heating curve for carrageenan at 1 % concentration is presented in Figure 4.3a. To look at the uniformity of heating, plots of temperature at different positions within the static ohmic heating cell are presented. Heating was uniform throughout the samples within experimental errors even though there was no mixing in the static ohmic heating cell. It is worth noting that time-temperature profiles for T1, T2, TC and TE were similar not only for carrageenan at all concentrations but also for all gelatin solutions (Figure 4.3b) and for pectin solutions at 1 and 3 % concentration. Profiles for xanthan (Figure 4.3c) as well as starch (Figure 4.3d) exhibited marked differences mainly between TE and all other thermocouples (T1, T2 and TC) which were in the same group. A similar trend was also observed for pectin solutions at 5 % concentration. Major differences between T1, T2, TC and TE were found for long heating periods, typical of the time/temperature profiles of starch solutions where one would expect more substantial heat losses to be occurring through electrodes locally. However, as compared to gelatin and pectin solutions, xanthan solutions exhibited a lower heating time.

De Alwis *et al.* (1989) found that during ohmic heating electrode surface temperatures were usually 2-3 °C lower than the bulk. They attributed this to the fact that the electrode can only heat by its resistance which is very low. It is only the conduction from the fluid that will cause the temperature rise. If the system is not well-mixed, temperature differences between the electrode and the bulk could be observed. Most experiments on ohmic heating of liquids dealt with low viscosity solutions. The assumption of a well-mixed system occurring in ohmic heating of low viscosity liquid



(a) carrageenan (1%)

(b) gelatin (2%)



(c) xanthan (2%)

(d) starch (6%)

Figure 4.3 Time-temperature profiles at 4 different locations in the cylinder (T1, T2, TC and TE) for selected hydrocolloids types and concentrations containing particulates in a static heater was predicted by computer simulations and verified experimentally (Fryer *et al.*, 1993). It has been reported that the issue of non-uniformities arises in static ohmic heating systems where there is a lack of convection in high viscosity solutions (Fryer *et al.*, 1993). Therefore, the non-uniformity explanation might rely on one other parameter that would also influence the heat transfer efficiency: the viscosity of solutions.

Viscosity effect

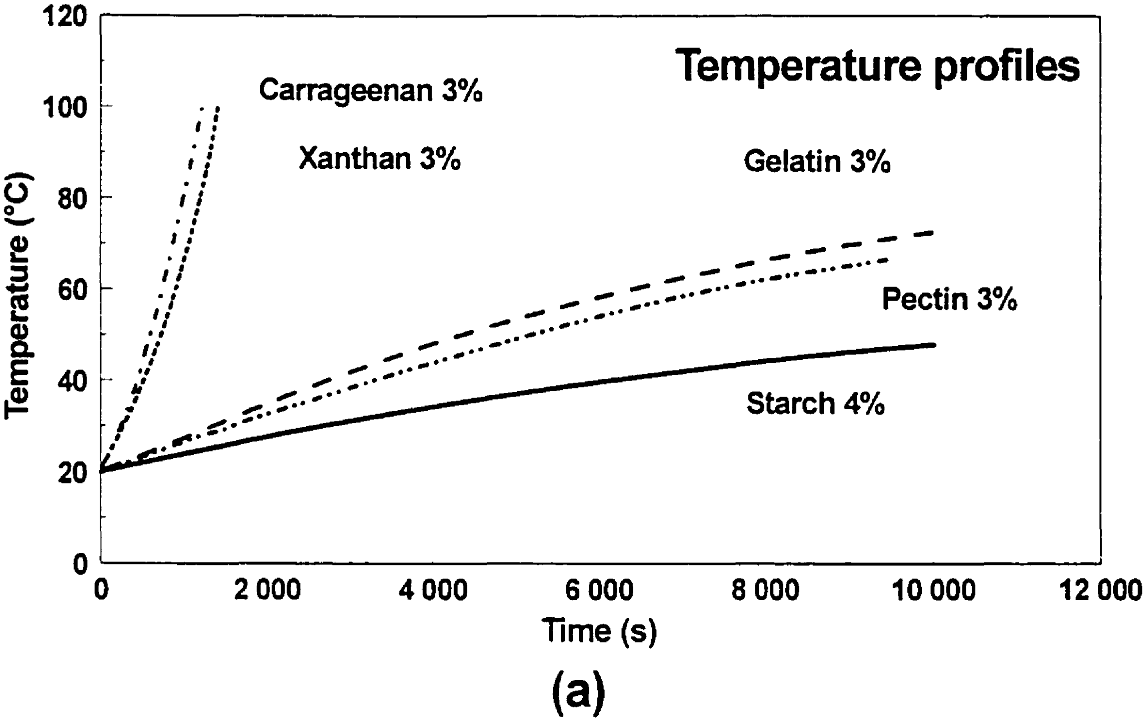
A power-law flow behaviour was observed with most test samples showing similar upward and downward curves. For some hydrocolloid solutions, a minimum value of shear stress or a yield was observed. The stress decay found in 10 min steady shear rate at 300 s^{-1} was small and therefore was neglected. Additional details on the rheological behaviour of the different hydrocolloid solutions were reported in Marcotte and Ramaswamy (1997). For the purpose of discussion of the viscosity effect, an apparent viscosity at a shear rate of 300 s^{-1} was computed. The apparent viscosity data for various hydrocolloids are summarised in Table 4.3 which indicates that it increased with concentration. On the other hand, as the temperature was increased, the viscosity decreased for all hydrocolloid types but by different extent. Carrageenan 2-3 %, gelatin 3-4 % and xanthan 3 % were gels at room temperature, but gelatin and carrageenan samples liquified quickly at around 40 °C. Below 4 % starch, the viscosity of the solution was too low to be considered as a thickening agent. Some fluctuations with shear stress - shear rate data were reported for 3 % starch. This was attributed to prevailing low viscosities (Abdelrahim, 1994). Rheological properties of xanthan remained stable even increasing slightly with respect to temperature which was also reported in the literature (Speers and Tung, 1986). The viscosity of pectin and starch decreased gradually when heated up. The effect of temperature was more important for pectin and starch solutions than for xanthan samples. The viscosity decreased as temperature increased. Due to the high viscosity values and less temperature dependency associated with starch and xanthan solutions, large temperature differences between T1, T2, TC and TE were observed with their ohmic heating behaviour.

Table 4.3 **Apparent viscosity (Pa.s) values at 300 s^{-1} at various temperatures for all hydrocolloid solutions at various concentrations**

Type	Concentration (%)	20°C	40°C	60°C	80°C
Carrageenan	1	0.037	0.017	0.013	0.010
	2	0.417	0.050	0.033	0.020
	3	0.750	0.167	0.073	0.050
Xanthan	1	0.067	0.067	0.073	0.073
	2	0.167	0.167	0.183	0.200
	3	0.267	0.267	0.267	0.333
Gelatin	2	0.017	0.006	0.006	0.005
	3	0.133	0.007	0.006	0.005
	4	0.583	0.009	0.007	0.006
Pectin	1	0.026	0.017	0.013	0.012
	3	0.333	0.183	0.117	0.067
	5	1.100	0.600	0.467	0.300
Starch	4	0.150	0.100	0.067	0.040
	5	0.417	0.267	0.183	0.117
	6	0.933	0.600	0.417	0.250

It has been reported that high viscosity solutions heat more quickly than water for the same electrical conductivities in a continuous ohmic heating system (Khalaf and Sastry, 1996). Natural convection has been shown to effectively reduce temperature differences in low viscosity solutions heated in a static ohmic cell (Fryer *et al.*, 1993). The same authors have also pointed out that predicting the heating rate of viscous materials is difficult in ohmic heating systems. For static-heater situations, reports (de Alwis *et al.*, 1989) revealed that the use of viscous carriers enhances ohmic heating as compared to the use of low viscosity fluids. Although viscous carriers have lower electrical conductivity than low viscosity fluids, the rate of increase of this property as a function of temperature was found to be sharper. This temperature enhancement of σ is believed to be the principal reason to enhance heating for high viscosity fluids as compared to low viscosity liquids (de Alwis *et al.*, 1989).

Ohmic heating temperature profiles and corresponding apparent viscosity profiles are plotted in Figure 4.4a and 4.4b on the same time scale so that they can be easily compared. A comparison of time/temperature profiles at 3 % concentration of hydrocolloids (4 % for starch) is presented in Figure 4.4a. Carrageenan gave the sharpest profile. It was closely followed by xanthan. Gelatin and pectin exhibited very similar time/temperature profiles. Starch samples never reached 100 °C. A comparison of apparent viscosity at 300 s^{-1} during the corresponding heating time is shown in Figure 4.4b for all hydrocolloid solutions. As expected, most values of apparent viscosity decreased with the heating time except for the xanthan solution. The lowering of viscosity as a function of heating time will generally favour faster heating of samples. Furthermore, rheological properties as influenced by concentration and temperature will definitely influence the uniformity of heating in the static ohmic heating cell especially for high viscosity solutions (e.g. xanthan and starch). In conventional thermal processing, the efficiency of the sterilisation relies on classical heat transfer phenomena or conduction and convection. If the concentration is increased, the viscosity will increase and the convection will be decreased. In contrast, increasing the concentration of hydrocolloids was found to favour faster heating of samples during ohmic heating under the conditions tested in this study. These results again suggest the dominant role of the electrical conductivity in the ohmic heating behaviour of hydrocolloid solutions. It



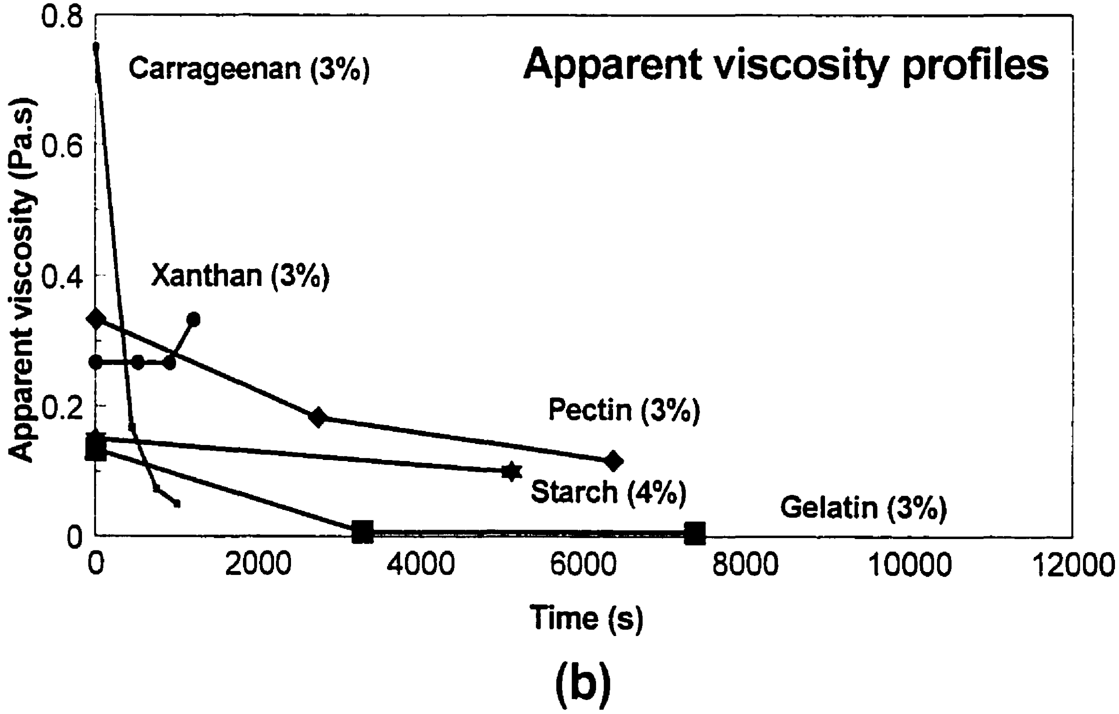
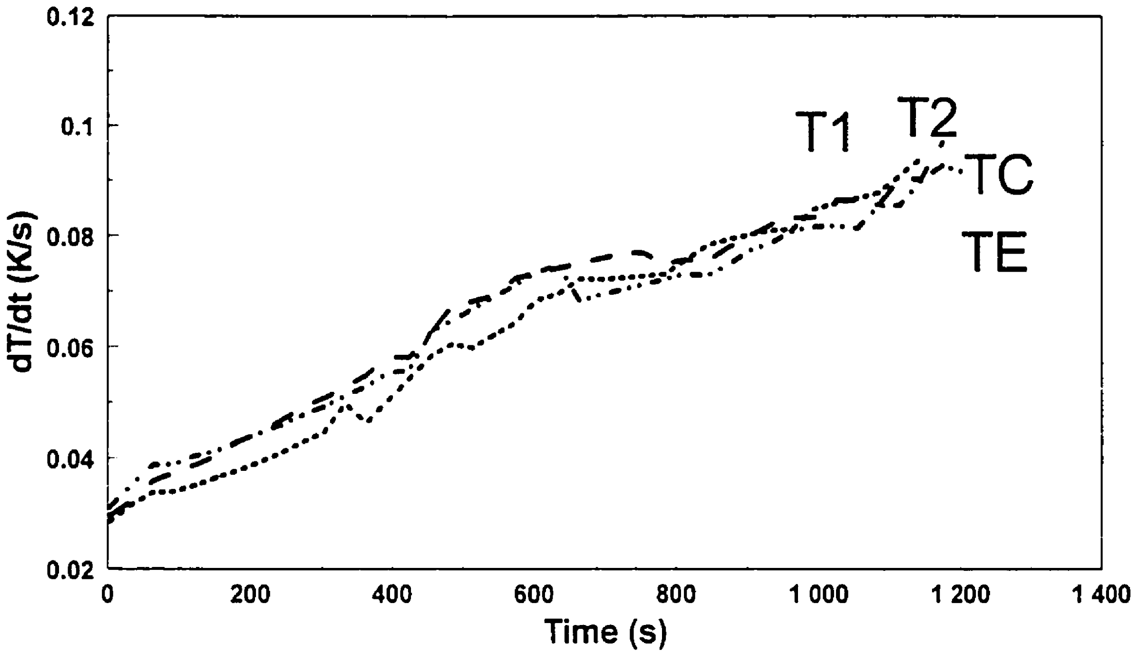


Figure 4.4 (a) Temperature profiles b) Apparent viscosities profiles (300 s^{-1}) during ohmic heating of hydrocolloid solutions at a comparable 3 % concentration

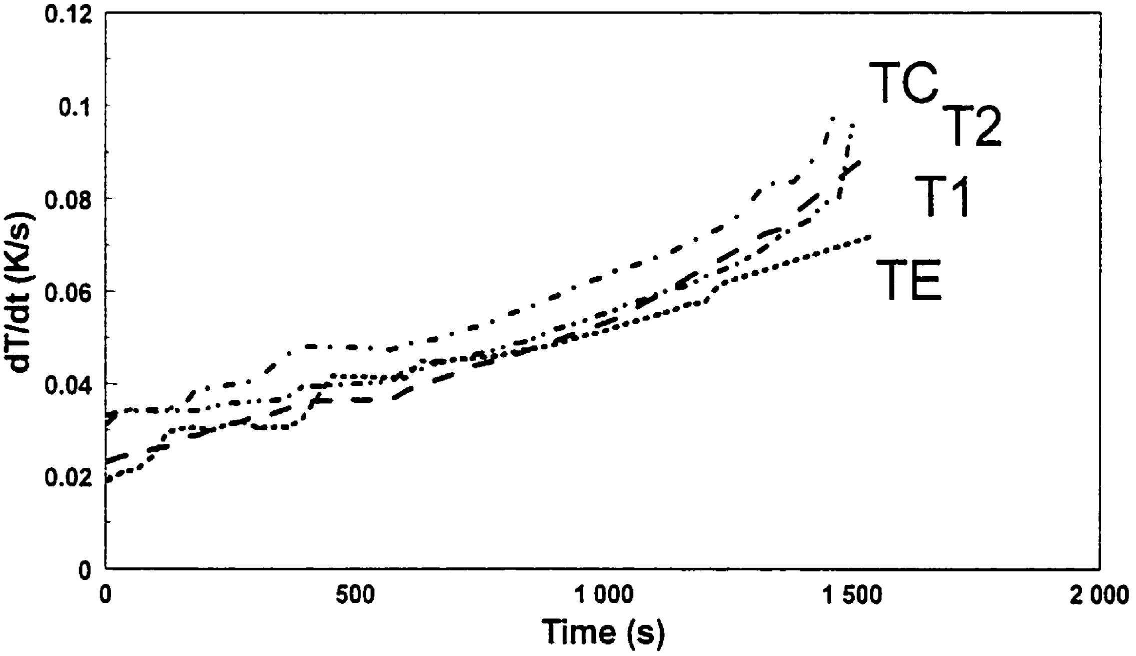
was reported earlier (Table 4.2) that the associated electrical conductivities of hydrocolloid solutions increased with concentration. The higher electrical conductivity associated with higher concentrations of these hydrocolloids appeared to dictate the heating rate of these solutions overriding the negative effect of increased viscosity on heating behaviour.

Heating rate

Experimental heating rates (dT/dt) are presented in Figure 4.5 for carrageenan and xanthan solutions at 3 %. They varied from 0.03 to 0.09 °C/s for carrageenan and 0.02 to 0.08 °C/s for xanthan. According to Stirling (1987), rapid heating of 1-5 °C/s should occur with electrical conductivity of 0.7-3 S/m and very rapid heating of 7-50 °C/s for 0.05-0.5 S/m. Both ranges correspond to our experimental values of electrical conductivities. Moreover, de Alwis and Fryer (1992) reported that within 1-5 S/m, a maximum of 0.8-4 °C/s heating rates should be observed on commercial ohmic heating units, which are continuous and operating at higher voltages. In industrial systems, voltages of 12000 V are readily available. In the APV ohmic heater the applied voltage is typically 3.3 kV per phase (Skudder and Biss, 1987) with a field strength of 18.3 V/cm. For these conditions, high heating rates (in the region of 1-10 °C/s) have been reported. A commercial residence time of less than 10-100 s is possible to obtain a temperature rise in the food of 100 °C. Moreover, with high viscosity solutions, the heating rate has been shown to increase substantially with field strength (8-20 V/cm) and an electrical conductivity (0.12-0.91 S/m) (de Alwis *et al.*, 1989). Our experimental field strength was slightly lower than 8 V/cm, (static ohmic heater) and much lower heating rates were measured. According to de Alwis *et al.* (1989), heating rates in a static cell would be lower than 0.05 °C/s for solutions having σ between 0.1 and 0.4 S/m at 20 °C. For high viscosity solutions having an electrical conductivity value of 0.9 S/m at 20 °C, higher heating rates of 0.2 °C/s were measured. Experimental values of electrical conductivity for our hydrocolloid solutions were less than 0.9 S/m at 20 °C in all cases which could explain why very low heating rates were measured. Therefore, results were in agreement to those reported by de Alwis *et al.* (1989).



(a) carrageenan



(b) xanthan

Figure 4.5 **Comparison of experimental heating rates at 3 % concentration for carrageenan and xanthan solutions.**

As pointed out by Sastry and Palaniappan (1992c), one of the most attractive features of the ohmic heating process is the potential to control heating rates by product design and formulation. Some hydrocolloids have been found to exhibit higher electrical conductivities than others with comparable apparent viscosity and concentration. Further studies are being conducted at optimising mixtures of hydrocolloid solutions to obtain proper electrical conductivities and at enhancing electrical properties of these solutions by the addition of salts or acids.

It can be deduced from the above discussion that the static ohmic heating system employed could be used to study the relative heating behaviour of the different hydrocolloid solutions. However, it should also be noted that heating rates obtained were rather low to be of practical use in high-temperature short-time aseptic processing applications. As discussed, the ohmic heating rates depend on associated electrical conductivities of the product, the electrical field applied and the geometric configuration of the system (i.e. ratio between the surface of electrodes and the distance separating the electrodes). Hence, these factors will have to be optimised for a particular food system involving the use of specific hydrocolloids.

CONCLUSIONS

The ohmic heating behaviour of selected hydrocolloid solutions was studied as influenced by temperature and concentration. Heating was more efficient as the concentration of hydrocolloids was increased. A trend opposite was observed for viscosities as being more viscous usually renders the fluid less susceptible to raise its temperature quickly. In most cases, heating was found to be uniform throughout the samples except at the electrodes where heat was lost. Non-uniformities were found to be related to rheological properties. Experimental heating rates were comparable to those reported in the literature for static ohmic heating cell experiments. Ohmic heating represents an efficient system for very viscous solutions and solid samples as compared to conventional heating.

CHAPTER 5

EFFECT OF SALT AND CITRIC ACID ADDITION ON ELECTRICAL CONDUCTIVITIES AND OHMIC HEATING BEHAVIOUR OF VISCOUS LIQUIDS

CONNECTING STATEMENT

The ohmic heating behaviour of selected hydrocolloids in solutions in a static cell was studied in chapter 4. At comparable concentrations, results indicated that heating rates were different depending on hydrocolloid types and concentrations. The observed heating behaviour of hydrocolloid solutions exhibited the same trend as their electrical conductivity values, which were discussed in Chapter 3. Heating was uniform at low viscosity but not for high viscosity solutions. The homogeneity of heating was related to the rheological properties of the hydrocolloid solutions and their behaviour at high temperatures (Chapter 4).

The aim of chapter 5 is to study the effect of salt and citric acid addition on electrical conductivities, time/temperature and heating rate profiles of selected hydrocolloids in solution having a standardised apparent viscosity of 0.2 Pa.s at 300 s^{-1} and 20 °C. As well, this study is used to evaluate the relative importance of formulation factors on the ohmic heating performance of these products.

The principal findings and conclusions presented in this chapter constitutes the manuscript entitled "Effect of salt and citric acid addition on electrical conductivities and ohmic heating behaviour of viscous liquids" that was submitted to the *Journal of Food Processing and Preservation.* The authors are: Michèle Marcotte (Ph.D. Candidate, who planned and conducted experiments, analysed results and wrote the manuscript), Hosahalli Ramaswamy (thesis supervisor, who guided the student, corrected, edited and revised the manuscript), Maher Trigui (who assisted in gathering data).

ABSTRACT

Four hydrocolloid solutions (starch, 4.3 %; carrageenan, 1.7 %; xanthan, 2 %; pectin, 2.5 %) were prepared in water with varying salt concentrations (0.25, 0.5, 0.75 and 1 %). Concentrations of hydrocolloids in solutions were previously adjusted to result in an apparent viscosity of 0.2 Pa.s at 20 °C. A constant initial voltage of 150 V was applied to each sample in a static ohmic heating cell to study the effect of hydrocolloid type and salt content on electrical conductivity and ohmic heating behaviour at their normal pH. As well, pH levels of these samples were modified by the addition of citric acid, and the combined effect of hydrocolloid type, salt content and citric acid was investigated. At low salt concentration, carrageenan and xanthan had the shortest heating time and the highest electrical conductivity values. This was followed by pectin samples. Starch was the least effective, having the slowest heating rate and lowest electrical conductivity values. At the highest salt concentration (1 %), the effect of salt overcame that of the hydrocolloid type giving similar time/temperature profiles and electrical conductivity values for all hydrocolloids. The effect of citric acid addition was present but negligible.

INTRODUCTION

Food formulations requiring hydrocolloids usually undergo a heat treatment to obtain a shelf stable product. Since these products are highly viscous, fouling problems often occur while using conventional thermal processing equipments. Ohmic heating has been foreseen as an alternative technology to provide the desired high-temperature short-time process in order to reduce the incidence of fouling. The heat treatment severity applied to food formulations in order to obtain a shelf stable product varies with pH (e.g. higher heat treatment will generally be required for low acid foods and the inverse applies for high acid foods). It has also been stated that acids could increase the ionic content render the food electrically more conductive (Skudder and Biss, 1987) thereby increasing the efficiency of the ohmic heating process. The relationship between acidity or pH on electrical conductivity has not been documented in the literature, although it is very important because it will influence the ohmic heating treatment time. Only Palaniappan and Sastry (1991b) reported values for fruit juices (i.e. low pH and low viscosity fluids).

Another important factor is the salt concentration in food formulations. It has been shown that the efficiency of ohmic heating increases with the salt concentration because it changes the electrical resistance that determines the heating rate (de Alwis and Fryer, 1992). Palaniappan and Sastry (1991a) soaked potato pieces in salt solutions at different concentrations and reported that as the concentration of salt absorption increased, the electrical conductivity values also increased with temperature as well as the resulting heating rates. The salt concentration in immersion solutions never exceeded 0.8 %. The relationship of σ–T was found to be linear. As well, Wang and Sastry (1993) investigated the effect of salt diffusion into potato tissue as a pretreatment for ohmic heating. Electrical conductivity profiles were found to follow the salt concentration profile. A stronger relationship between σ-salt concentration was found when the salt concentration exceeded 0.01 g/cm^3 in the tissue. Use of high concentration brine resulted in non-linear σ-T profiles during ohmic heating and quadratic models were obtained. The effect of the salt content of fish food emulsions (e.g. surimi), was included by Yongsawatdigul *et al.* (1995b), as an important parameter in their model for electrical conductivity as influenced by composition and temperature. The level of NaCl was found to significantly affect the electrical conductivity values in frozen seafood during ohmic thawing, the treatment being more efficient at higher concentrations of salt (Luzuriaga and Balaban, 1996). Kim *et al.* (1996a) reported that the effect of salt on electrical conductivity of viscous fluids, which are normally used as carrier liquids in conventional aseptic processing and ohmic heating, had not been widely studied. The same authors also reported that the salt content of the sauce or gravy of a typical particulate foods (e.g. beef stew) is usually between 0.6-1 %.

The objective of this work was to study the effect of salt concentration (0.25, 0.50, 0.75 and 1.0 %) and citric acid addition (normal and modified pH) on electrical conductivities and ohmic heating behaviour of selected hydrocolloids in water.

MATERIALS AND METHODS

Type and concentration of hydrocolloids

Four hydrocolloids were chosen for this study: carrageenan (Grinsted Carrageenan, CL210, Danisco Ingredients Canada, Rexdale, ON, Canada), xanthan (Rhodigel, lot # 9635001, Rhone-Poulenc Food Ingredients, Washington, PA, USA), pectin (Grinsted Pectin, RS400 lot # 701J547, Danisco Ingredients Canada, Rexdale, ON, Canada), starch (Thermo-flo starch, NFPA 0934 lot # LF5919, National Starch and Chemical Corp., Bridgewater, NJ, USA).

Dry hydrocolloid powders were weighed and thoroughly mixed with the appropriate amount of salt (NaCl) for final concentrations (0.25, 0.5, 0.75 and 1%) before being incorporated into hot water at 80°C. The dry mixture of salt/hydrocolloid was added slowly in small quantities to the hot water, mixed with a hand blender and heated on a hot plate until it reached 100°C. These samples were poured into 500 ml glass jars, cooled and stored for further analyses. The whole procedure was repeated twice. The solutions obtained were at their normal pH [e.g. carrageenan, (pH: 8.8); starch, (pH: 8.8); xanthan, (pH: 6.3) and pectin, (pH: 3.5)] that was measured.

Further to the above preparation procedure, citric acid was added to the mixture of dry hydrocolloid/salt in order to modify the pH of hydrocolloid solutions. These solutions were identified as modified pH solutions. For carrageenan and starch, the pH was adjusted to 6.5-6.8 as they are normally used for low acid foods. For xanthan and pectin, the modified pH was around 2.8 to represent acidic conditions prevalent in fruit products.

Rheological measurement

The apparent viscosity of each hydrocolloid solution was determined using a rotational viscometer (Rotovisco, Model RV20, Haake Mess-Technik, Karlsruhe, Germany) equipped with an M5 OSC measuring head and a MV2 rotor. Samples were loaded into the cylindrical cup and allowed to equilibrate at 20°C for 20 min in a water bath. A computer controlled program (Rheocontroller, RC20 module, Haake Mess-Technik, Karlsruhe, Germany), in the rotational mode, was used to shear samples at a linear rate from 0 to 300 s^{-1} in 3 min. Silicone oil standards (Cannon Instrument Company, State College, PA, USA) were used to calibrate the rheometer. Shear stress - shear rate data were gathered as rheograms. Apparent viscosities were calculated at 300 s^{-1} in Pa.s for each hydrocolloid type and concentration as a ratio of the experimental shear stress over the constant shear rate of 300 s^{-1}. Experiments were carried out in triplicate. The appropriate concentration of each hydrocolloid was determined by trials and errors to obtain the same apparent viscosity at 20 °C at a shear rate of 300 s^{-1}. The final concentration was found to be 1.7 % for carrageenan, 2.5 % for pectin, 4.3 % for starch and 2 % for xanthan.

Electrical conductivity and time/temperature profiles

Electrical conductivity measurements and time/temperature profiles of test samples were carried out in a static ohmic heating cell schematically shown earlier in Figure 4.1a and reproduced here in Figure 5.1a to provide continuity. The procedure used for calculating electrical conductivity and gathering time/temperature profiles is detailed in Chapters 3 and 4. Briefly, a 400 ml sample of hydrocolloid solution was introduced into the static ohmic heating unit, which consisted of a glass cylinder of 2.48 cm diameter and 20.69 cm length. Two titanium electrodes were located at extremities of the cylinder. A constant voltage of 150 V was applied with a maximum allowable current of 5 A. Four type-T Teflon coated thermocouples were fitted to the glass cylinder for solution temperature measurement. One thermocouple was placed close to the electrode, one at the centre of the cylinder and two placed at mid-point between the centre and the electrode in opposite directions. Voltage, current and temperature were recorded at specific time intervals using a datalogger (Model Hydra 2625A, John Fluke MFG Co. Inc., Everett, WA) connected to a computer, over a temperature range of 20-80 °C. Electrical conductivity was calculated from the resistance (R=V/I) of the sample and the geometry of the cell (Palaniappan and Sastry, 1991a):

$$\sigma = \left(\frac{1}{R}\right)\left(\frac{L}{A}\right) x\ 100 \qquad [5.1]$$

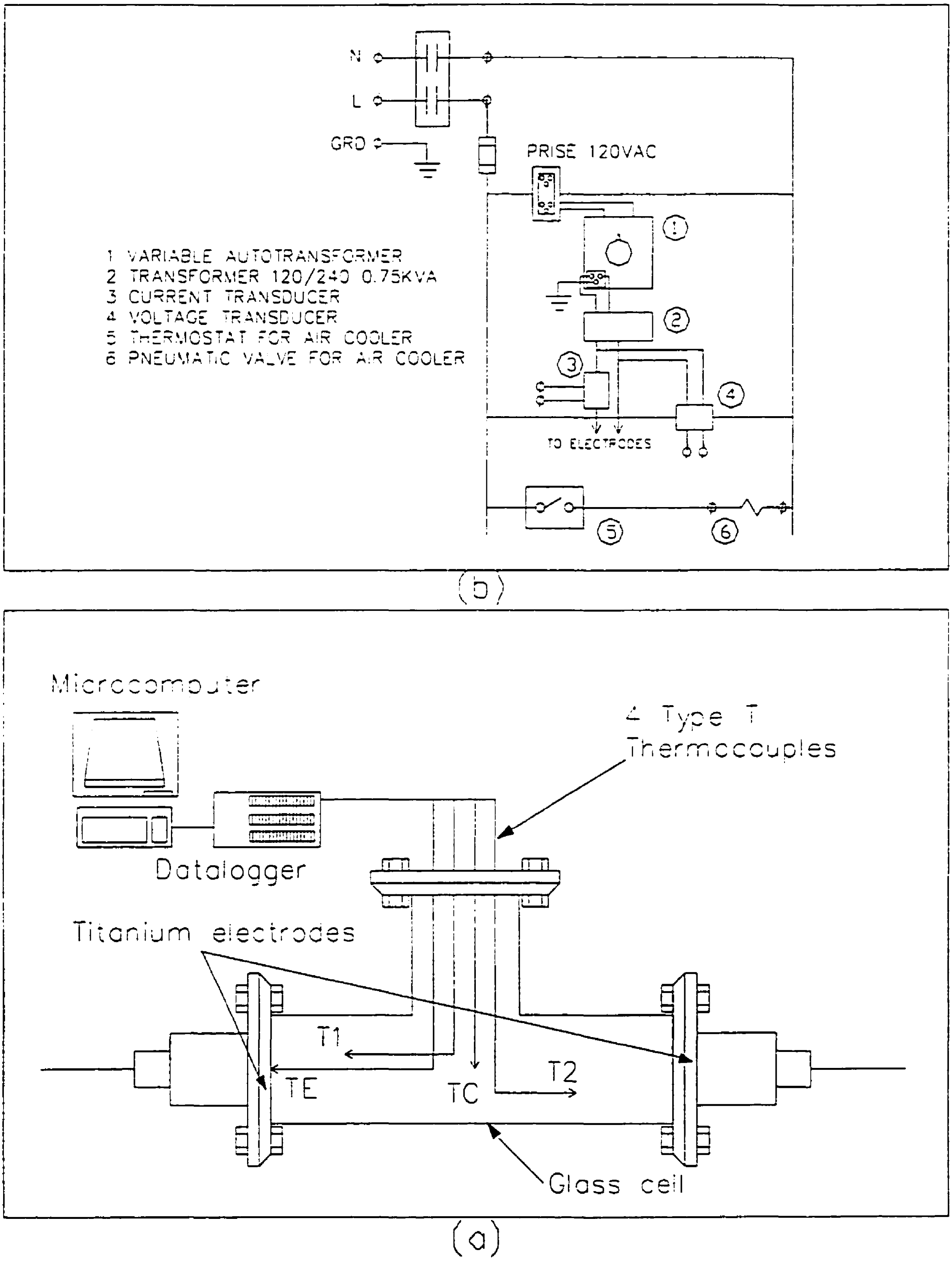


Figure 5.1 (a) Schematic of the static ohmic heating cell
(b) Details of the electrical circuit

Heating rates were obtained by calculating the slopes of the curve of temperature against time, giving values of dT/dt directly at different processing times. First derivatives (dT/dt) at a given t were computed using a commercial software package (TableCurve2D, Version 4, SPSS Inc., Chicago, IL).

Data analysis

A statistical analysis computer program (SAS Institute Inc., Cary, NC) was first used to test for the statistical significance of the main effects (i.e. product type, salt content (SC), the acid content (AC) taken as pH and the temperature (T)) on the electrical conductivity. For each hydrocolloid type, an analysis of variance was also performed to identify significant factors (e.g. T, SC, AC) on electrical conductivity and heating rate. The model also included the interaction effects. For each hydrocolloid type, a regression model on electrical conductivity and heating rate was established including second order polynomial terms (T^2, SC^2, AC^2) if significant. A plot of residuals was evaluated to ensure that both the assumptions of constant variance and normality were satisfied.

RESULTS AND DISCUSSION

Time/temperature profiles

Time/temperature profiles of four hydrocolloids at normal pH as influenced by salt concentration, processed at 150 V with varying current up to 5 A, are presented in Figure 5.2. Time/temperature profiles of starch (4.3 %), carrageenan (1.7 %), pectin (2.5 %) and xanthan (2 %) at normal pH and four levels of salt (0.25, 0.5, 0.75 and 1 %) are shown at a comparable viscosity of 0.2 Pa.s at 20°C and 300 s^{-1}. Regardless of the type of hydrocolloid, as the concentration of salt increased, the profiles became steeper. The lower the salt concentration, the more the time was required to reach 80 °C. Heating rates were observed to increase with temperature as a result of increasing electrical conductivity analogically as in Sastry and Palaniappan (1992c). Less than 900 s were required for all products to increase their temperature to 80 °C.

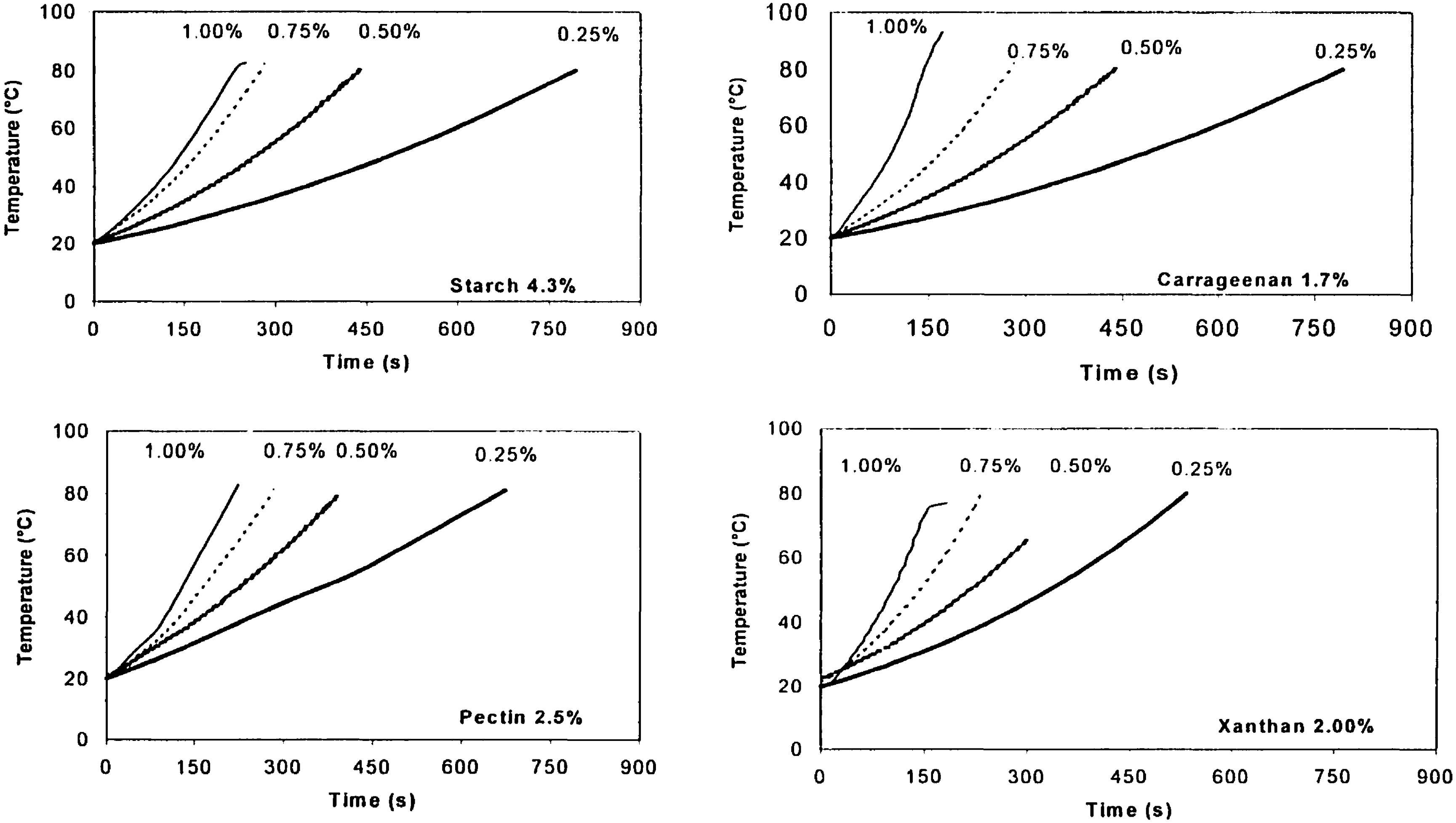


Figure 5.2 Effect of salt concentration (0.25, 0.5, 0.75 and 1 %) on temperature profiles of four hydrocolloid types (pectin 2.5 %, xanthan 2.0 %, starch 4.3 % and carrageenan 1.7 %) at normal pH

Heating profiles of the different hydrocolloids at a comparable viscosity (i.e. 0.2 Pa.s at 20 °C and 300 s^{-1}) and selected salt concentrations are compared on Figure 5.3. Similar heating patterns were observed for all products. At low salt concentration (0.25 %), carrageenan and xanthan heated faster than pectin and starch. Starch had the slowest heating behaviour. Time/temperature profiles became much similar as the concentration of salt was increased for all products indicating a greater effect of the salt during ohmic heating. As the concentration was increased, the salt addition dominated the time/temperature profiles, presumably as a result of increased electrical conductivity.

A comparison of the time/temperature profiles for carrageenan, xanthan, pectin and starch at normal and modified pH is presented on Figure 5.4. Profiles for modified pH products were slightly sharper than the ones for normal pH. This can be explained by the addition of the weakly charged citric acid. However, the addition of citric acid did not have a major effect when compared to the salt content and the hydrocolloid type effects.

Heating rates for all hydrocolloid types were determined as a function of temperature and are shown in Figure 5.5. Heating rates were found to increase linearly as a function of the temperature. For starch (4.3 %) and pectin (2.5 %), they varied from 0.05 °C/s (0.25 % salt and 20 °C) to 0.35-0.45 °C/s (1 % salt and 80 °C) respectively. At 20 °C, steeper rates (0.1 °C/s) were observed for xanthan (2 %) and carrageenan (1.7 %) at 0.25 % salt (a low concentration). Heating rates at 1 % salt and 80 °C were the highest (0.65 °C/s) for carrageenan (1.7 %). Another factor that will strongly affect heating rates is the field gradient (7.24 V/cm) that was considered to be low but typical of static ohmic heating systems. Similar heating rates were reported for viscous solutions at 8 V/cm with similar electrical conductivities (de Alwis *et al.*, 1989). Heating rates, that were obtained, can be considered small. To a certain extent, they were increased by a factor of 4 by increasing the salt concentration from 0.25 to 1 % at 20 °C. At 80 °C, the effect of the salt concentration on heating rates was more important, as heating rates were increased 5 times.

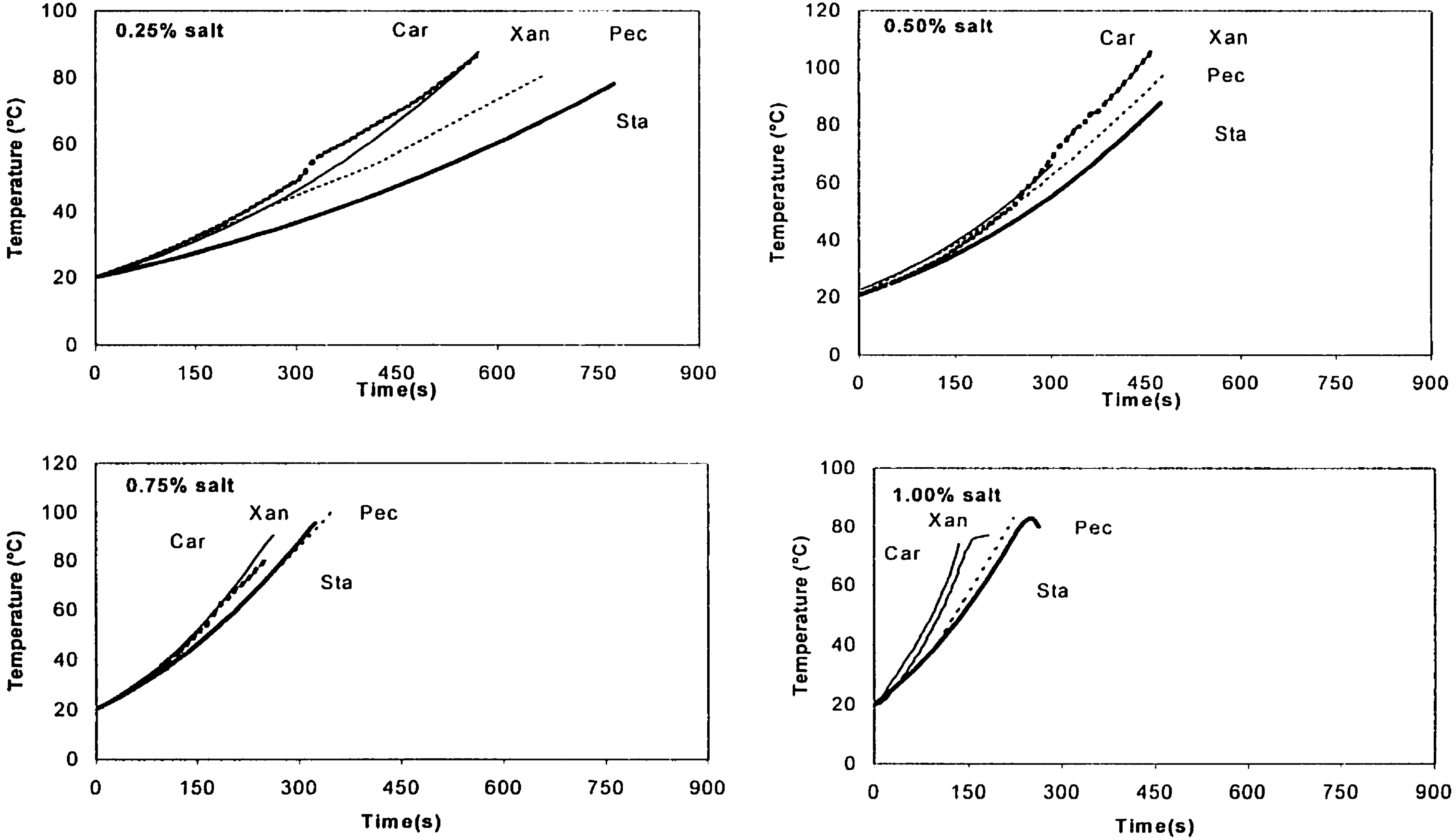


Figure 5.3 Effect of hydrocolloid types (starch, 4.3 %; carrageenan, 1.7 %; pectin, 2.5 % and xanthan, 2 %) on temperature profiles at normal pH at 0.25, 0.5, 0.75 and 1 % salt concentration

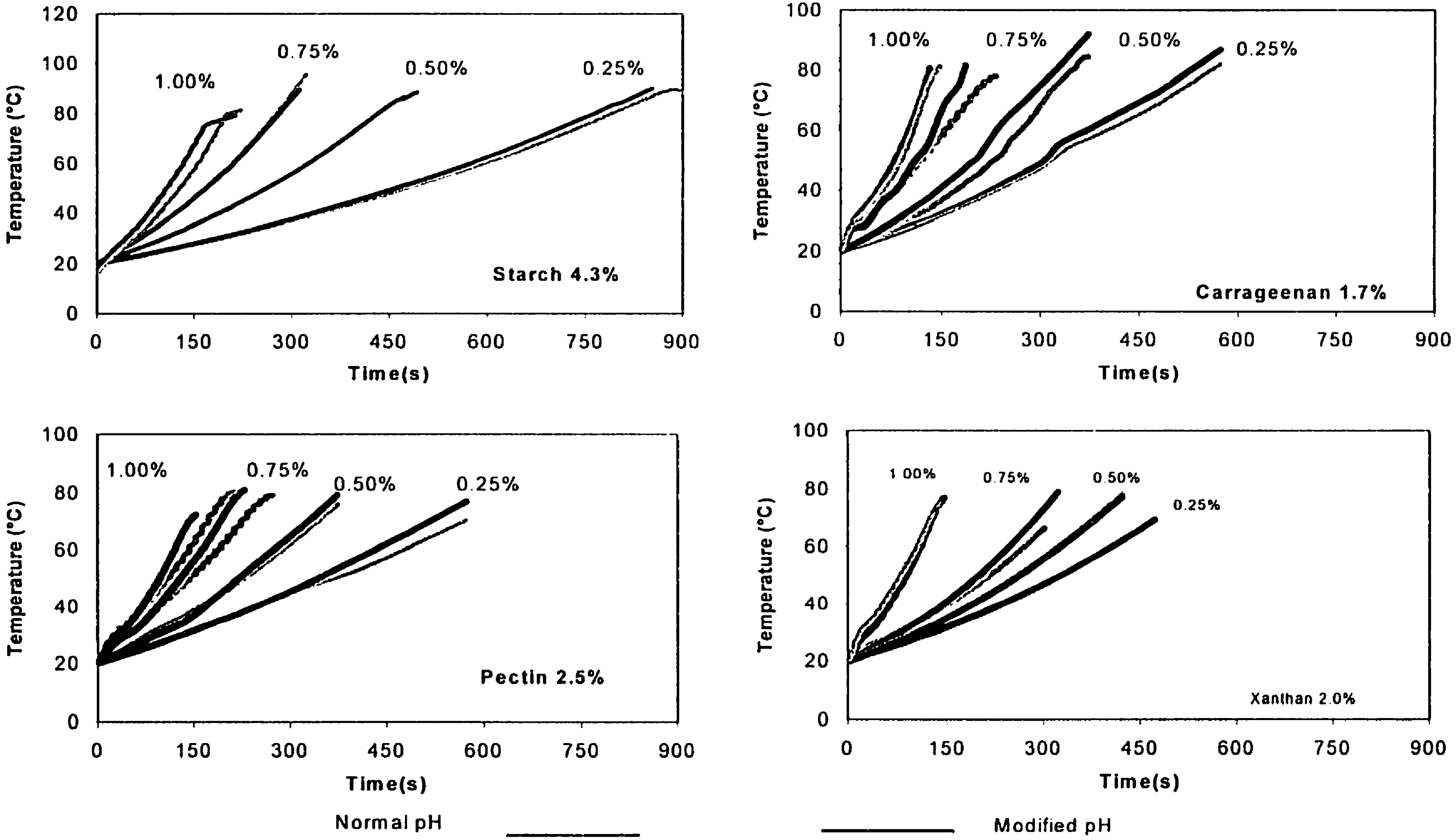


Figure 5.4 Effect of citric acid addition on temperature profiles at normal and modified pH for starch 4.3 %, carrageenan 1.7 %, pectin 2.5 % and xanthan 2.0 %

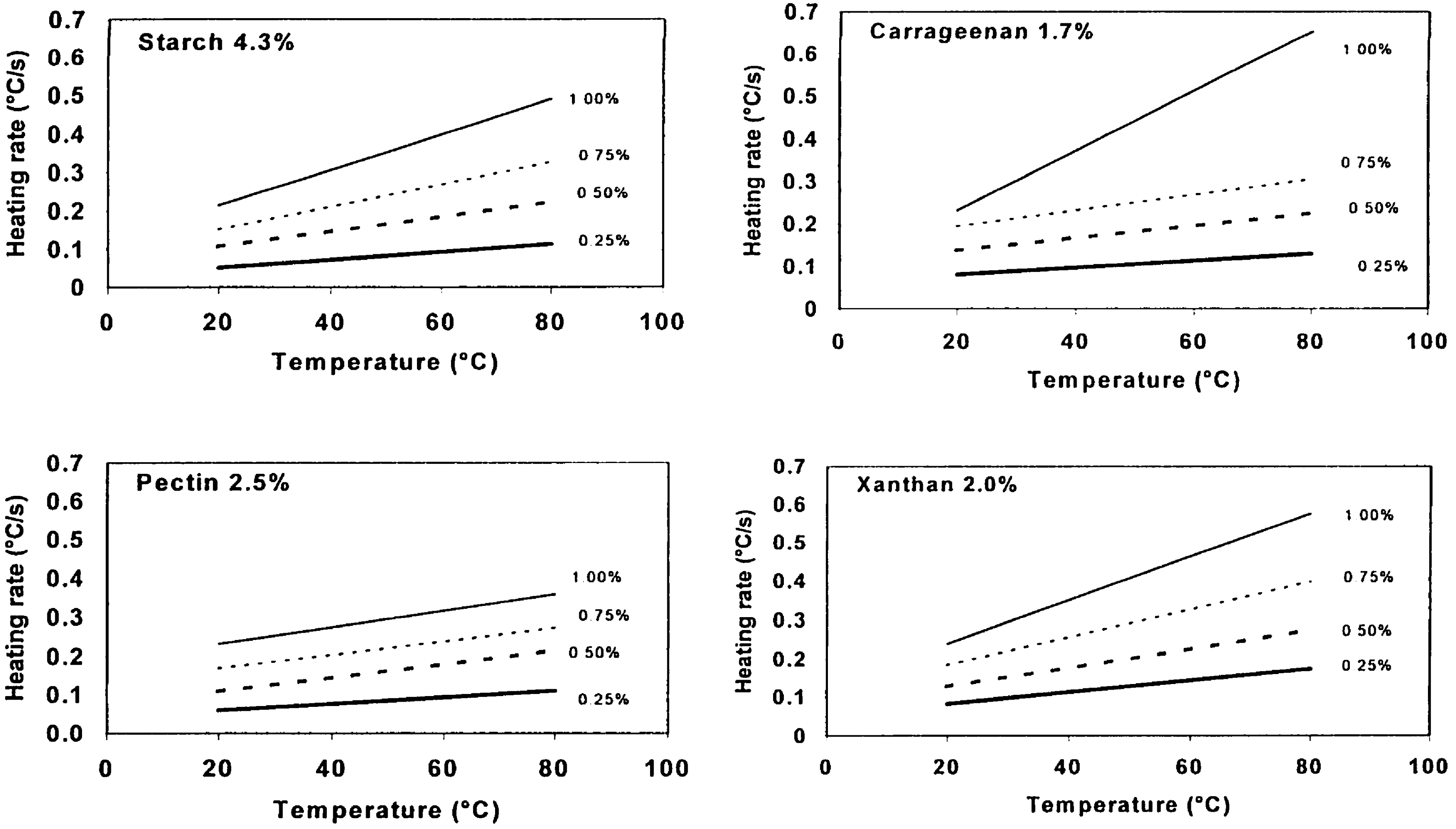


Figure 5.5 Heating rates of four hydrocolloid types (starch 4.3 %, carrageenan 1.7 %, pectin 2.5 % and xanthan 2 %) in solutions at 0.25, 0.5, 0.75 and 1 % salt concentration

Electrical conductivity

The effect of salt concentration on electrical conductivity at normal pH for different products (starch, carrageenan, pectin and xanthan) is presented in Figure 5.6. Electrical conductivity increased linearly with temperature. Several authors (Palaniappan and Sastry, 1991ab; Yongsawatdigul *et al.*, 1995b) have reported similar behaviour. As the salt concentration increased, so did the electrical conductivity. The effect is more pronounced at high temperatures. This particular pattern was observed for all hydrocolloid solutions.

Electrical conductivity vs. temperature profiles of four hydrocolloids at a comparable viscosity level (0.2 Pa.s at 20 °C) are compared in Figure 5.7. Electrical conductivity varied linearly with temperature for all hydrocolloid solutions. However, starch had the lowest electrical conductivity over the entire temperature range at 0.25, 0.50 and 0.75 % concentration. Electrical conductivity profiles for pectin were slightly higher than those for starch. Xanthan and carrageenan had similar electrical conductivity profiles.

Values of electrical conductivities for 4.3 % starch with salt addition, at 0.25 and 0.5 % at 20 °C, were found to be 0.5 and 1 S/m respectively. These were similar to those reported by Kim *et al.* (1996a) for 5.5 % starch with a similar salt concentration of 0.2 %, 0.55 % being 0.34 and 1.3 S/m, respectively at 19 °C. They also reported electrical conductivities of 5.5 % starch solutions at 2 % salt as 4.3 S/m. According to Kim *et al.* (1996a), the salt content of a typical gravy used for a beef stew is 0.6-1.0 %. In this particular case, the level of salt is sufficient to overcome the differences in hydrocolloid types upon ohmic heating. However, this would not be the case for fruit based products in which increasing the concentration of salt up to 1 % would be objectionable to the taste.

Fryer *et al.* (1993) used three solutions of CMC at low viscosity (0.018 Pa.s), medium viscosity (0.064 Pa.s) and high viscosity (0.8 Pa.s) having a similar standardised initial electrical conductivity of 0.95 S/m at 20 °C in their study of heat generation and convection effects in ohmic heating. Results obtained under static ohmic heating for solutions showed a linear temperature dependence with almost identical temperature coefficients of electrical conductivity. From our results, in order to obtain 0.95 S/m at

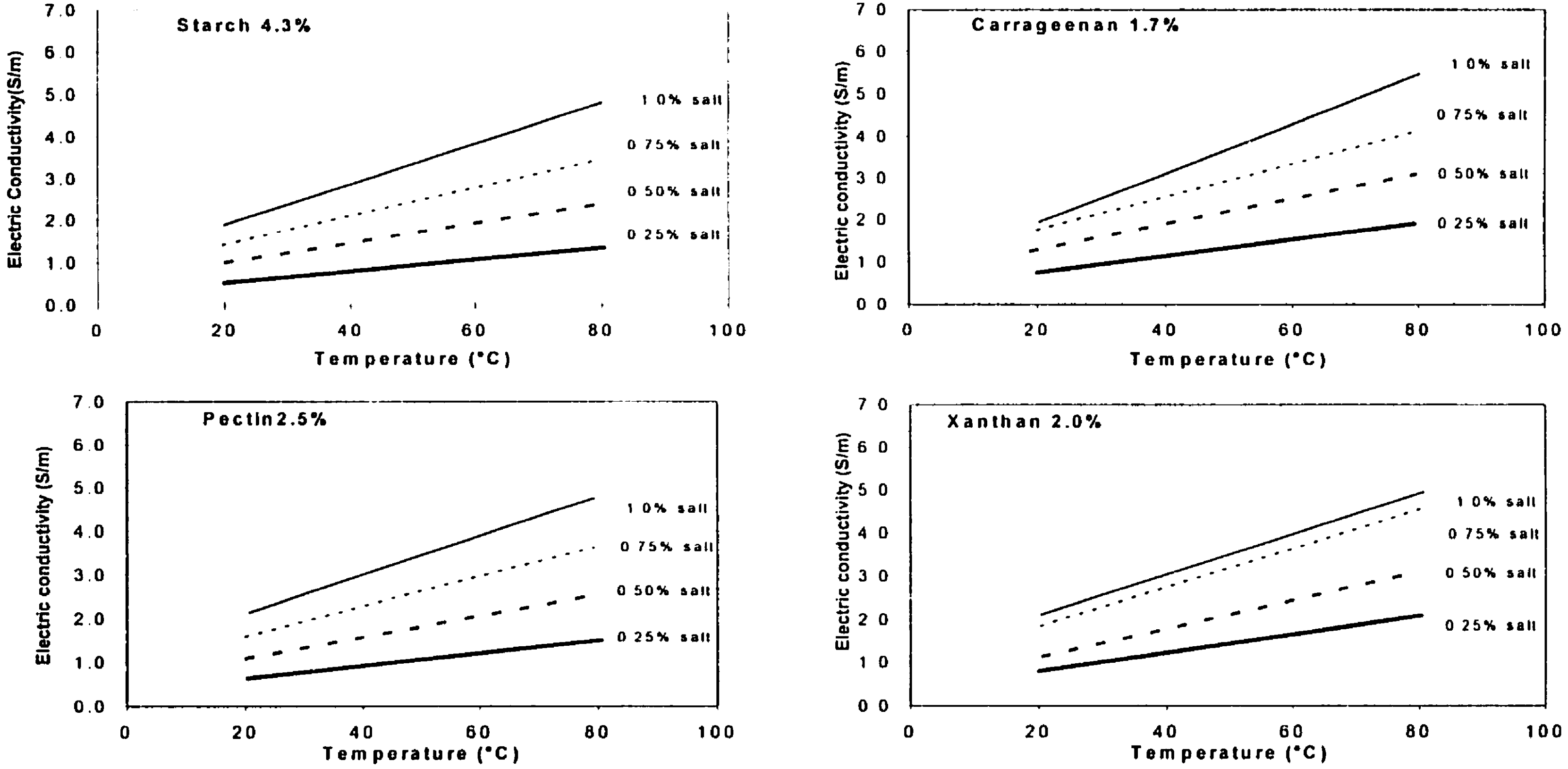


Figure 5.6 Effect of four salt concentrations (0.25, 0.5, 0.75 and 1 %) on electrical conductivities of four viscous liquids (starch 4.3 %, carrageenan, 1.7 %, pectin 2.5 % and xanthan 2.0 %)

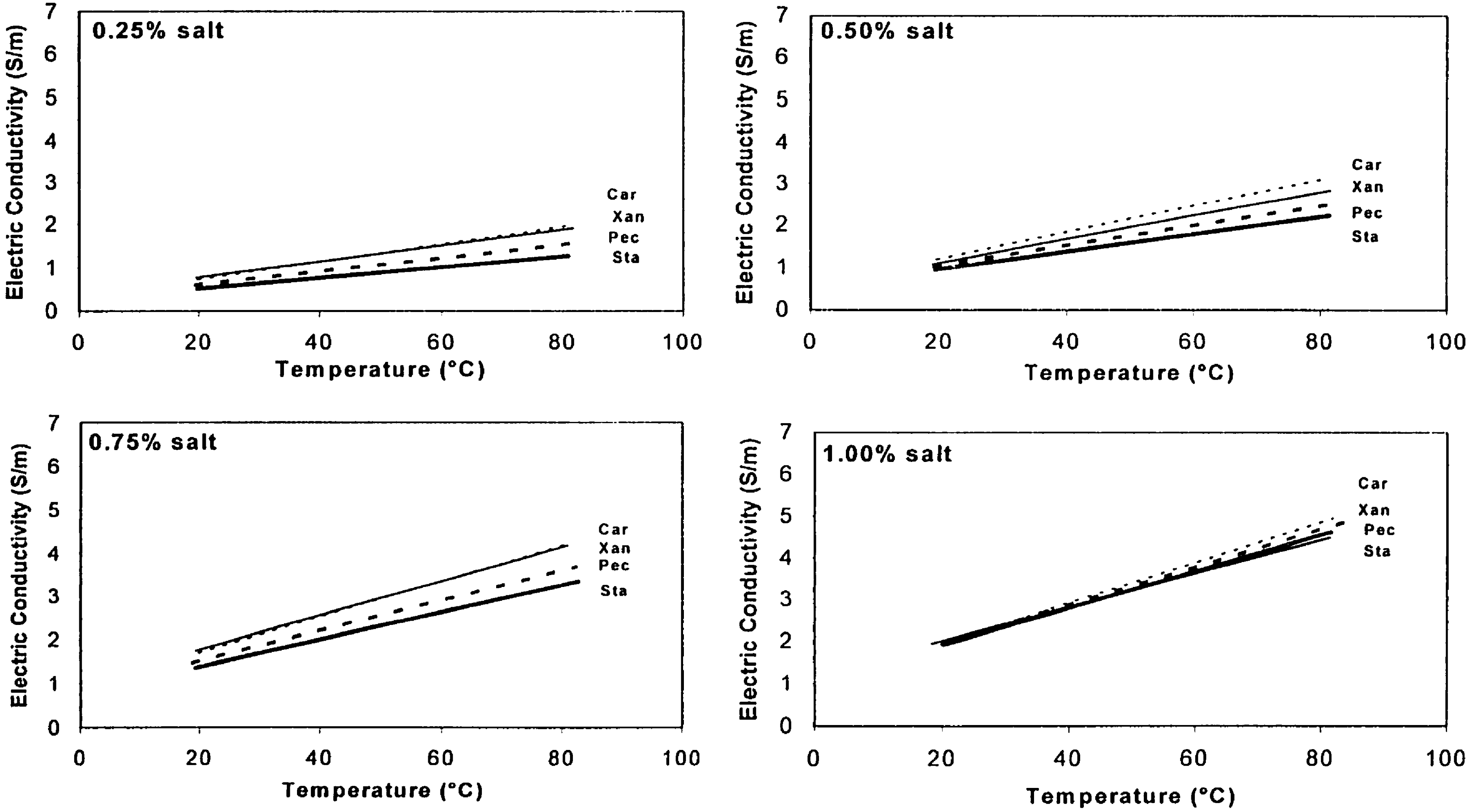


Figure 5.7 Effect of four hydrocolloid types (starch 4.3 %, carrageenan 1.7 %, pectin 2.5 % and xanthan 2 %) on electrical conductivities at 0.25, 0.5, 0.75 and 1 % salt concentration

20 °C, an addition of salt greater that 1 % would be necessary. Results have shown that as the concentration of salt was increased to 1 %, electrical conductivities and ohmic heating rates were influenced more by the salt addition and less by the composition of hydrocolloid solution.

The effect of added citric acid on electrical conductivities at normal and modified pH for different hydrocolloids revealed that there was little difference (results not shown). The effect of citric acid addition both for electrical conductivity and heating profiles was also found to be small. Citric acid is an organic acid that is not strongly dissociated. Even though large pH differences were determined, it was not sufficient to show any differences in electrical conductivities and heating profiles.

At low salt concentration (0.25 %), carrageenan and xanthan solutions heated at the same rate (Figure 5.3) which also confirmed by their similar values of electrical conductivity (Figure 5.6). The rate of heating of pectin was slower and that of starch followed next. The magnitude of electrical conductivity values and heating profiles were largely influenced by hydrocolloid type at low salt concentration, which may be related to the chemical structure and composition of these hydrocolloids. Palaniappan and Sastry (1991b) indicated that the nature of ions and the ionic movement of liquid samples can affect electrical conductivities. Carrageenans are acidic hydrocolloids always accompanied with counter ions. The structure of xanthan renders this hydrocolloid anionic. These charged compounds could explain their better efficiency upon ohmic heating at low salt concentration. Most starches are usually a combination of amylose and amylopectin in different proportions. It is usually a neutral polysaccharide, which could explain it being the poorest performer upon ohmic heating. Pectin is a polymeric carbohydrate composed of a chain of galacturonic acid units that are partially esterified as methyl esters. Therefore, it will be less charged than xanthan and carrageenan but more so than starch. The structure of these hydrocolloids can explain the specific ohmic heating behaviour at low salt concentration.

As the salt concentration was increased to 0.5, 0.75 and 1 %, the hydrocolloid effect is reduced resulting in similar heating electrical conductivity profiles for all hydrocolloid solutions. Yongsawatdigul *et al.* (1995b) reported a similar trend on the effect of salt on surimi paste during ohmic heating. As the concentration of salt was increased from 1 to 4 %, electrical conductivity profiles vs. temperature were sharper. Similar values of electrical conductivities, to ours, were observed for their surimi paste at 1 % salt concentration and 75 % moisture content. At 20 °C, the electrical conductivity was 1 S/m and at 80 °C 5 S/m, whereas our value for starch, pectin and xanthan was 2 S/m at 20 °C increasing to 5 S/m at 80 °C. The heating rate of the surimi emulsion was higher than for our hydrocolloid solutions. Sastry and Palaniappan (1992c) also pointed out a greater temperature effect for solids than for fluids upon ohmic heating. Surimi paste is more of an emulsion than a liquid. Therefore, a greater temperature effect was expected.

An analysis of variance of the electrical conductivity data indicated that the type of hydrocolloids, the salt concentration and the temperature (main effects) were significant along with their significant two way interactions (e.g. type*pH, type*salt, type*temperature, pH*salt and salt*temperature) as seen in Table 5.1. pH, as a main effect, had generally no influence ($p>0.05$) on electrical conductivity. The variance linked to the salt concentration term was the largest. It was followed by the variance associated with the temperature. All other terms were relatively less important. Contrasts were computed and revealed that the effect of temperature as well as the effect of salt concentration was linear. Regressions were obtained for each hydrocolloid type including a salt and temperature effect and the interaction between salt and temperature. Results are presented in Table 5.2.

In their statistical analysis of the data, Yongsawatdigul *et al.* (1995b) observed an interaction between the salt and the water content. Moreover, electrical conductivities increased quadratically with salt content and there was a significant interaction between the salt content and the temperature. Our data show only a linear effect for salt. This might be due to the fact that concentration was varied from 0.25 to 1 % whereas for Yongsawatdigul *et al.* (1995b) the salt concentration varied over a broader range from 1 to 4 %.

Regression parameters were computed for the combined effect of salt concentration and temperature on electrical conductivity and heating rate. For all hydrocolloid types, salt content, temperature and the interaction between salt content and temperature were significant for electrical conductivity. However, only the salt

Table 5.1 **Analysis of variance for the effect of hydrocolloid types, salt and acid content and temperature on electrical conductivities**

Source	DF	Sums of square	F Value	Pr > F
Model	255	593.84825038		
type	3	13.63788765	345.39	0.0001
pH	1	0.00002636	0.00	0.9643
salt	3	278.39487932	7050.61	0.0001
temp	7	261.53370964	2838.68	0.0001
type*pH	3	0.49533301	12.54	0.0001
type*salt	9	1.74413108	14.72	0.0001
type*temp	21	2.18807114	7.92	0.0001
pH*salt	3	1.16000670	29.38	0.0001
pH*temp	7	0.04921290	0.53	0.8083
salt*temp	21	31.48187702	113.90	0.0001
Type*pH*salt	9	2.02067115	17.06	0.0001
Type*salt*temp	63	0.42758846	0.52	0.9989
pH*salt*temp	21	0.07417605	0.27	0.9996
Type*pH*salt*temp	84	0.64067991	0.58	0.9981
Error	256	3.36940592		
Total	511	597.21765631		

Table 5.2 **Regression parameters for electrical conductivities and experimental heating rates for each type of hydrocolloids at 0.25, 0.5, 0.75 and 1% salt concentration**

Type	Salt Concentration (%)	σ_{25} (S/m)	$K_{\sigma T}$ (S/m°C)	r^2	R_{20} (°C/s)	K_{rT} (1/s)
Carrageenan (1.7%)	0.25	0.848	0.0199	0.9531	0.08077	0.00083
	0.50	1.371	0.0313	0.9840	0.13856	0.00146
	0.75	1.914	0.0413	0.9959	0.19520	0.00185
	1	2.173	0.0481	0.9915	0.23182	0.00703
Xanthan (2%)	0.25	0.889	0.0181	0.9630	0.08241	0.00155
	0.50	1.474	0.0305	0.9837	0.12812	0.00246
	0.75	1.969	0.0396	0.9294	0.18535	0.00357
	1	2.162	0.0419	0.9747	0.23939	0.00562
Pectin (2.5%)	0.25	0.691	0.0153	0.9619	0.05874	0.00085
	0.50	1.201	0.0261	0.9312	0.10817	0.00180
	0.75	1.690	0.0349	0.9938	0.16953	0.00173
	1	2.195	0.0455	0.9963	0.23266	0.00210
Starch (4.3%)	0.25	0.582	0.0123	0.9959	0.05120	0.00103
	0.50	1.066	0.0204	0.9828	0.10691	0.00194
	0.75	1.544	0.0312	0.9763	0.15101	0.00294
	1	2.109	0.0427	0.9999	0.21339	0.00461

$$\sigma = \sigma_{25} + K_{\sigma T}(T-25)$$

$$R = R_{20} + K_{RT}(T-20)$$

concentration and the combined effect of temperature and concentration were significant for heating rates. Values of regression parameters for electrical conductivities and heating rates are listed in Table 5.3 and were used to plot surface response curves in Figure 5.8 and Figure 5.9. These two figures demonstrate the similarity between electrical conductivity and heating rates under the context of ohmic heating, both increasing with temperature and salt content.

CONCLUSIONS

Results of the study indicated that at low salt concentration (<1 %) in a water-based system, the type of hydrocolloids will have an impact on electrical conductivity values and time/temperature profiles. Charged hydrocolloids like carrageenan and xanthan are more efficient than pectin and starch upon ohmic heating. With salt concentration at or greater than 1 %, the salt effect is more important than the type of any hydrocolloid in solutions. The effect of citric acid addition both for electrical conductivities and heating profiles was found to be small.

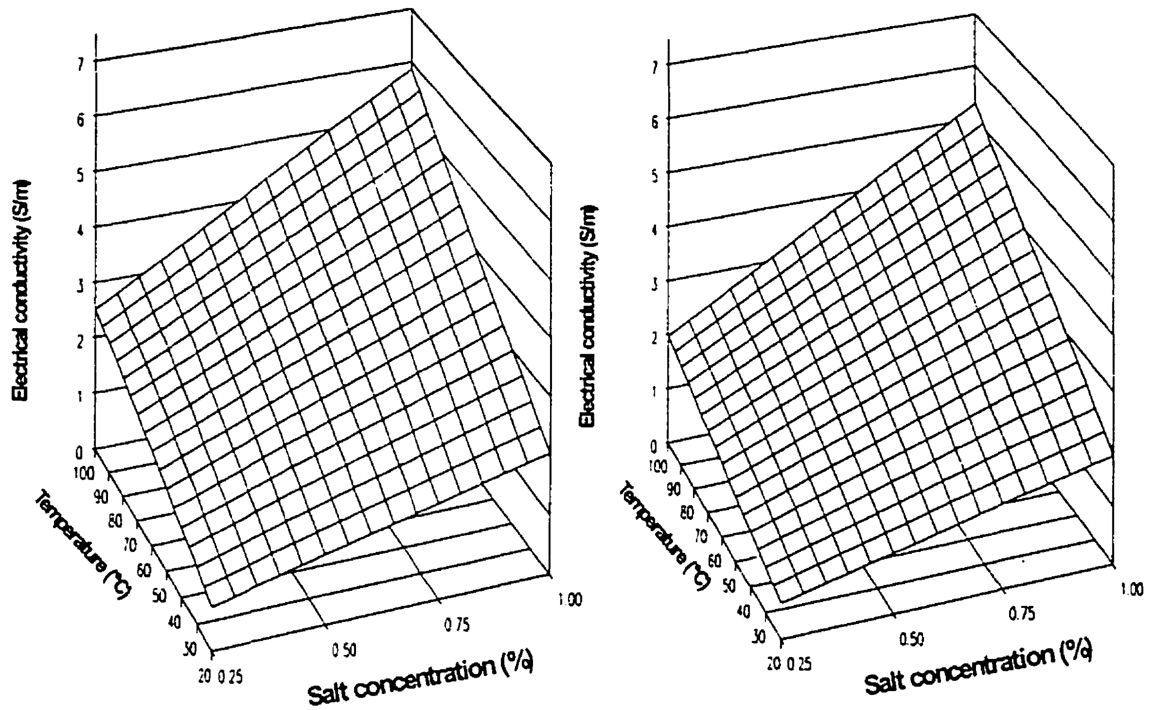
Table 5.3 Regression parameters for each type of hydrocolloids at salt concentration and combined salt concentration-temperature effects

ELECTRICAL CONDUCTIVITY

Type	Estimates	Parameter values	r^2
Carrageenan	Salt	1.08 ± 0.03	0.9978
	Temperature	0.014 ± 0.005	
	Salt*Temperature	0.034 ± 0.001	
Xanthan	Salt	1.15 ± 0.05	0.9941
	Temperature	0.0130 ± 0.0008	
	Salt*Temperature	0.033 ± 0.002	
Pectin	Salt	1.04 ± 0.04	0.9968
	Temperature	0.0085 ± 0.0005	
	Salt*Temperature	0.034 ± 0.001	
Starch	Salt	1.01 ± 0.03	0.9980
	Temperature	0.0016 ± 0.0004	
	Salt*Temperature	0.0417 ± 0.0008	

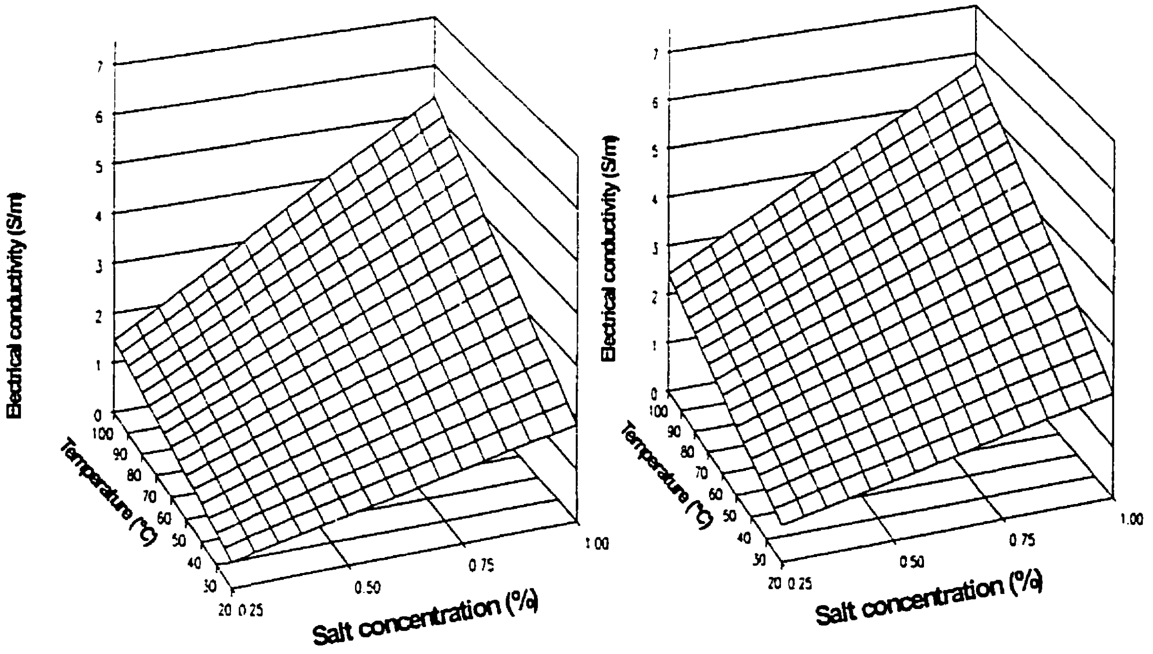
HEATING RATES

Type	Estimates	Parameter values	r^2
Carrageenan	Salt	0.13 ± 0.01	0.9830
	Salt*Temperature	0.0063 ± 0.0003	
Xanthan	Salt	0.148 ± 0.007	0.9924
	Salt*Temperature	0.0043 ± 0.0002	
Pectin	Salt	0.147 ± 0.009	0.9784
	Salt*Temperature	0.0037 ± 0.0003	
Starch	Salt	0.120 ± 0.006	0.9923
	Salt*Temperature	0.0044 ± 0.0002	



(a) carrageenan

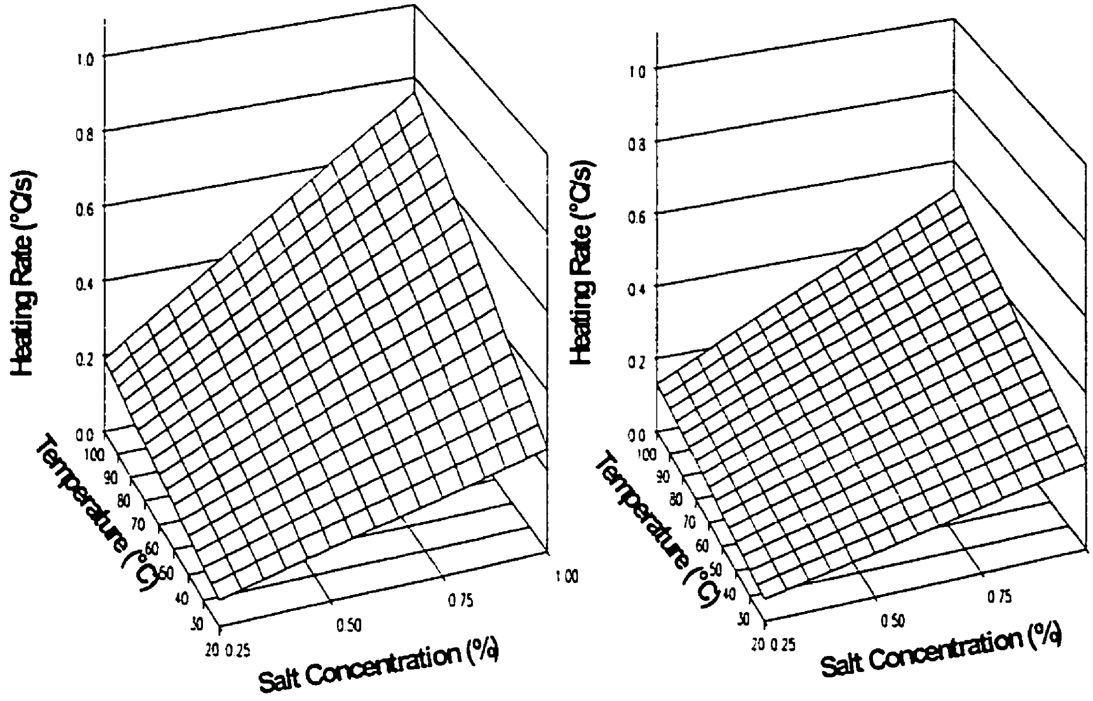
(b) pectin



(c) starch

(d) xanthan

Figure 5.8 Response surface plots for electrical conductivities as a function of salt concentration and temperature for all hydrocolloid types



(a) carrageenan

(b) pectin

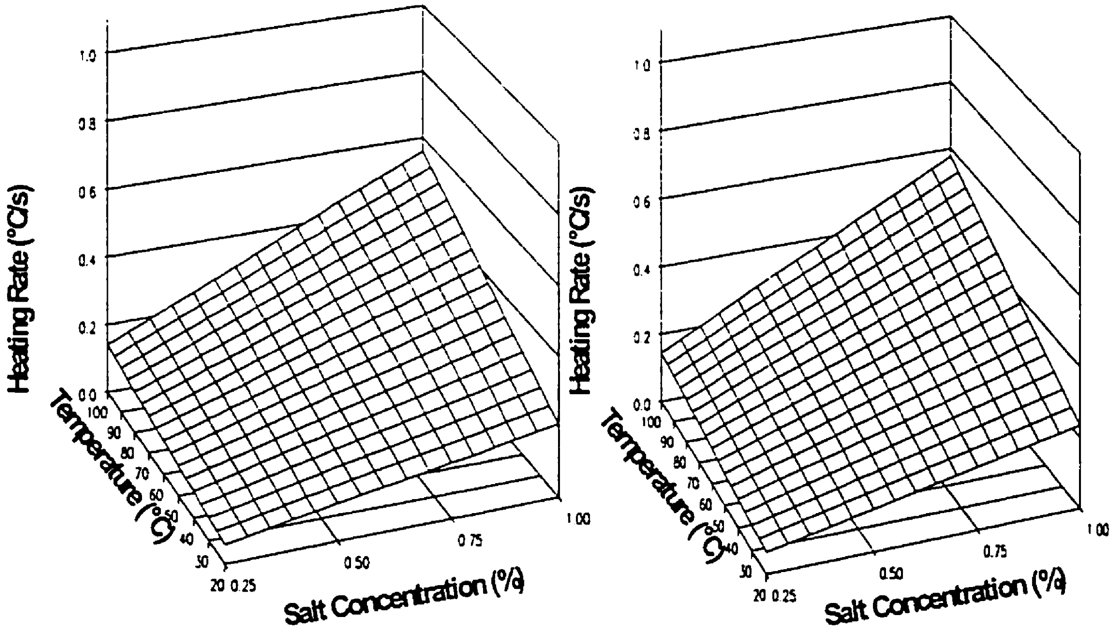


Figure 5.9 Response surface plots for heating rates as affected by the salt concentration and the temperature for all hydrocolloids

CHAPTER 6

PHYSICAL PARAMETERS (VOLTAGE GRADIENT, DISTANCE BETWEEN ELECTRODES AND CROSS-SECTIONAL SURFACE AREA OF ELECTRODE AFFECTING ELECTRICAL CONDUCTIVITY, TIME/TEMPERATURE PROFILE AND HEATING RATE DURING OHMIC HEATING OF HYDROCOLLOID SOLUTIONS

CONNECTING STATEMENT

In previous chapters, formulation factors of selected hydrocolloids in aqueous solutions were studied with respect to their effect on electrical conductivities, time/temperature profiles and heating rates. Hydrocolloid types did affect electrical conductivities and heating behaviour. As well, it was found that at low salt concentration, there was an interaction between the hydrocolloid type and salt on electrical conductivities and heating rates. At 1 % salt concentration, the hydrocolloid type did not have any impact on these parameters.

After having studied the formulation factors, this study was undertaken to evaluate the static cell configuration factors and their effects on electrical conductivities and heating rates. Hence, this chapter deals with the role of voltage gradient, cross-sectional surface area of electrodes and distance between electrodes on electrical conductivities and heating rates.

A large portion of the text presented in this chapter was submitted to *Journal of Food Science* as "Parameters affecting electrical conductivities, temperature profile and heating rate during ohmic heating of hydrocolloid solutions". The authors are: Michèle Marcotte (Ph.D. Candidate, who planned and conducted experiments, analysed results and wrote the manuscript), Hosahalli Ramaswamy (thesis supervisor, who guided the student, corrected, edited and revised the manuscript), Maher Trigui (who assisted in carrying out experiments and to gathering of data).

ABSTRACT

Several parameters (voltage gradient, distance between electrodes and cross-sectional surface area of electrodes) were studied for their effect on electrical conductivity, time/temperature profiles and heating rates during ohmic heating of selected hydrocolloid solutions in a static system. Voltage gradient had the major effect on the time/temperature profiles but no effect on electrical conductivities. As the voltage gradient increased, time/temperature profiles were steeper. A minimum voltage gradient of 15 V/cm was necessary in order to obtain the same heating rate as in conventional heating with the exception of xanthan which showed a better performance even at 5.26 V/cm. Due to high and temperature stable viscosity, xanthan solutions heat very slowly under conventional heating and hence could dramatically benefit from ohmic heating. Similar time/temperature profiles were obtained for a given distance between electrodes even though the cross-sectional surface area of electrodes nearly doubled. Increasing the cross-sectional surface area of electrodes had a negligible effect on time/temperature profiles, while increasing the distance between electrodes had a major impact. Current was observed to be the limiting factor in some conditions as 10-12 A was quickly attained. Experimental time/temperature profiles and heating rates were found to match computer simulations of a developed theoretical model, which could then be used to simulate other conditions and establish design criteria for static cells.

INTRODUCTION

There is limited experience in ohmic heating of foods on an industrial scale, therefore, all possible parameters that could be involved must be considered in the process design. Many of these parameters can be found in conventional heating processes but their magnitude and effect may be different. As well some, like electrical properties, are very specific, but essential (de Alwis and Fryer, 1992) to the design of electrical processes. De Alwis and Fryer (1992) demonstrated that there is an operating range of electrical conductivities, balanced between voltage and applied current, which results in a desirable temperature rise in foods. Most pumpable foods contain sufficient water and dissolved ionic species such as salts and acids which render them electrically conductive to benefit from ohmic heating (Halden *et al.*, 1990). Moreover, food formulations can be adjusted by mixing highly conductive or resistive food ingredients so that the required overall conductivity can be achieved for the best efficiency of the ohmic heating process within existing physical limits of voltage and current.

Electrical conductivities of liquids are usually calculated from the resistance and the geometry of the measurement cells. The resistance is obtained from the voltage and the current. Since transformers and other electrical equipment have limitations on current, an optimal geometric configuration must be designed to achieve the desired electrical conductivity at practical voltage levels. Therefore, to best utilise the available power, the electrical conductivity of the product has to be carefully evaluated in the design.

Liquid electrical conductivities are commonly evaluated with commercial conductivity meters. In its simplest form, this measurement involves the determination of the resistance between two electrodes of a fixed shape at a constant distance. Usually the current is measured when a fixed voltage is applied. The relationship between the electrical conductivity of the liquid and the resistance across the electrodes includes a cell constant (i.e. ratio of distance between and area of the electrodes, L/A). It is a common practice to maintain the resistance between limits of 10 and 100000 ohms. Since food materials have been reported to have a wide range of electrical conductivities, from 10^{-3} to about 10^{2} S/m (de Alwis *et al.*, 1989; Stirling, 1987), cell constants could vary from 1 to 50 cm^{-1} (Cummings and Torrance, 1985). Most food liquids would necessitate a practical cell constant of 50 cm^{-1}. In order to measure the electrical conductivity, it is necessary to know the cell constant accurately. The usual practice is to measure the resistance when the cell is filled with a solution whose conductivity is accurately known. For reference purposes, aqueous solutions of potassium chloride are normally used. Crow (1979) reported that for high conductivities, a high cell constant would be used to increase the sensitivity of the measurement (i.e. small electrodes and large distance between electrodes). For small conductivities, the ratio L/A should be very small. Large electrodes are used and the length between electrodes is kept short. Several authors (Crow, 1979; de Alwis *et al.*, 1989; Palaniappan and Sastry, 1991b; Yongsawatdigul *et* *al.*, 1995b) have reported that there is no effect of voltage gradient on electrical conductivities of liquids.

Time/temperature profiles in static heaters are strongly influenced by electrical conductivities and by the geometry of the ohmic unit. Fryer *et al.* (1993) investigated the ways in which ohmic heating of liquids differs from conventional thermal processing in a static heater for low and high viscosity fluids by making use of analytical solutions. They found that the model based on an infinite conduction and convection heat transfer and uniform electrical conductivity with a temperature relationship was in good agreement with experimental results for low viscosity liquids. They stated that predicting the heating rate of viscous fluids was still difficult. De Alwis *et al.* (1989) found that heating rates were strongly influenced by field strength and electrical conductivity. They also observed that enhanced heating rates were obtained with high viscosity solutions of the same electrical conductivity, due to higher temperature coefficients of electrical conductivity for viscous solutions.

Several parameters are interrelated and will determine the geometry of the device used not only for electrical conductivity measurements but also for ohmic heating of commercial formulations. Information generated is used to understand the interactions of parameters for the proper design of ohmic heating equipment. Such data may help in scale-up considerations in industrial set-ups.

The objective of this work was to study the effect of various parameters, which affect the electrical conductivity in the context of ohmic such as the voltage gradient, the distance between electrodes and the cross-sectional surface area of electrodes in static cell experiments. Time/temperature profiles and heating rates, as affected by the same parameters, were also studied simultaneously.

MATERIALS AND METHODS

Sample preparation

Four hydrocolloids were obtained from local sources: carrageenan (Grinsted Carrageenan, CL210, Danisco Ingredients Canada, Rexdale, ON, Canada), xanthan

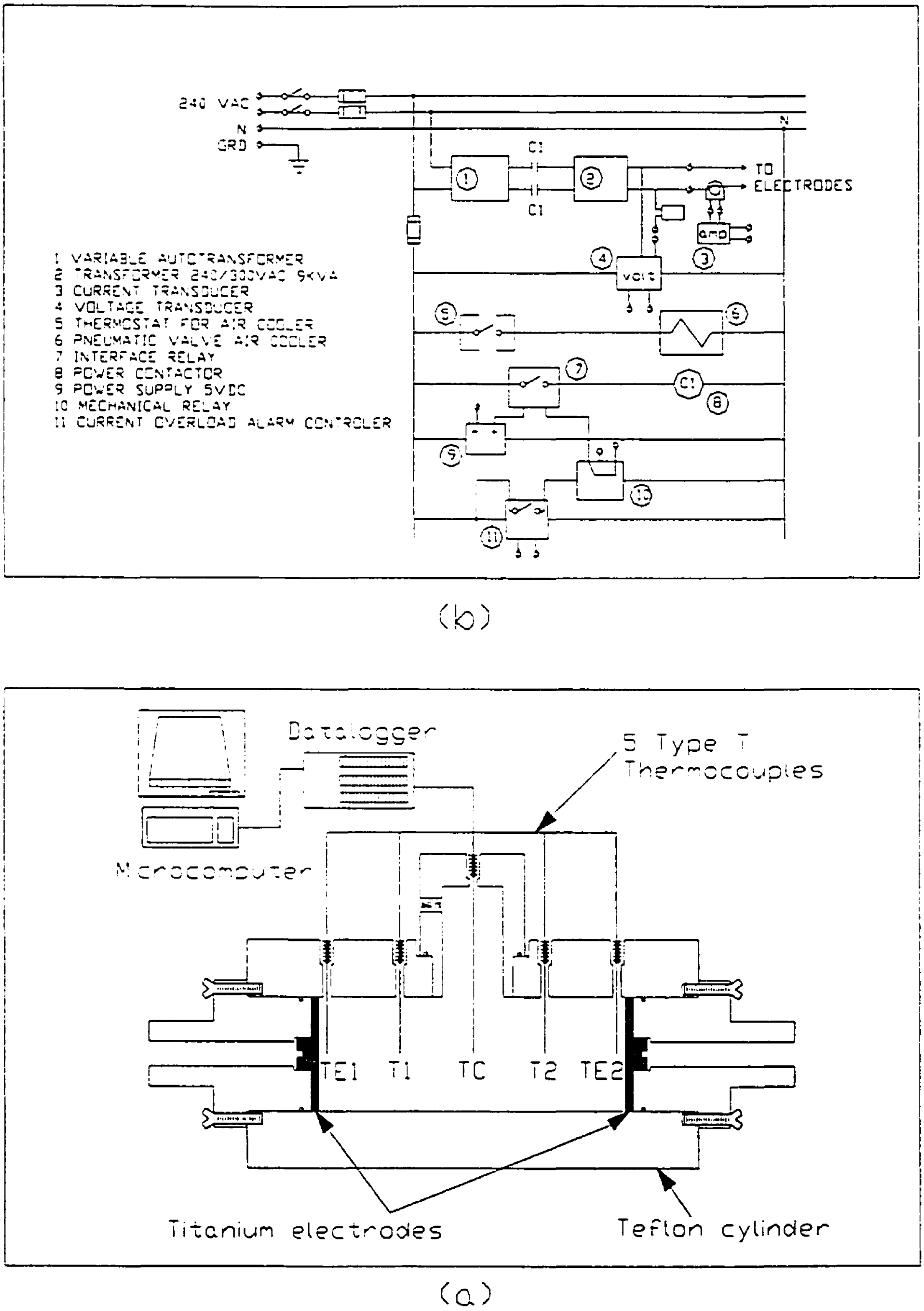
(Rhodigel, lot # 9635001, Rhone-Poulenc Food Ingredients, Washington, PA, USA), pectin (Grinsted Pectin, RS400 lot # 701J547, Danisco Ingredients Canada, Rexdale, ON, Canada), starch (Thermo-flo starch, NFPA 0934 lot # LF5919, National Starch and Chemical Corp., Bridgewater, NJ, USA).

The concentration of each hydrocolloid in water was previously determined to obtain an apparent viscosity of 0.2 Pa.s at 300 s^{-1} and 20 °C: starch, 4.3 %; carrageenan, 1.7 %; xanthan, 2 % and pectin, 2.5 %. Apparent viscosities of hydrocolloid solutions were determined using a rotational viscometer (Rotovisco, Model RV20, Haake Mess-Technik, Karlsruhe, Germany) equipped with an M5 OSC measuring head and a MV2 rotor. Solution samples were loaded into the cylindrical cup and allowed to equilibrate at 20 °C for 20 min in a water bath. A computer controlled program (Rheocontroller, RC20 module, Haake Mess-Technik, Karlsruhe, Germany) in a rotational mode was used to shear samples at a linear rate from 0 to 300 s^{-1} in 3 min. Salt concentrations were adjusted between 0.5-1 %.

A batch of 4500 g of solution was prepared for each hydrocolloid. Pre-weighed amounts of powder and salt (to yield the appropriate concentration in the final product) were thoroughly mixed and slowly dispersed into hot water (80 °C) while being continuously stirred. The mixture was then heated to 98 °C to complete the dissolution. For thermo-flo starch, it was autoclaved in a pilot retort at 137 °C for 15 min to complete the gelatinization. Air bubbles were removed by centrifuging hot mixtures at 1500 rpm.

Experimental set-up

Two different static ohmic heating cells were used in this experimental protocol: a small and a large Teflon cell. A schematic of the typical Teflon cell is illustrated in Figure 6.1a. Five type T Teflon coated thermocouples were fitted perpendicularly to the Teflon cylinder. Two thermocouples were placed close to each electrode. Two thermocouples were placed mid way between the centre of the cylinder and the electrodes in each direction and one thermocouple was placed at the centre. Table 6.1 summarises the geometric parameters of the two cells.



(b)

(a)

Figure 6.1 a) Schematic of the Teflon ohmic heating cell
b) Drawing of the electrical circuit

Table 6.1 Geometric dimensions of Teflon cells

Name	Cross-sectional Surface area (cm^2)	Distance (cm)	Volume (cm^3)
Small Teflon cell			
S1L1[1]	19.85	10.05	200
S1L2[2]	19.85	14.33	285
S1L3[3]	19.85	20.00	400
Large Teflon cell			
S2L1[4]	37.97	10.05	380
S2L2[5]	37.97	14.33	545
S2L3[6]	37.97	20.00	760

[1] S1L1 : smallest cross-sectional surface area (19.85 cm^2) and smallest distance (10.05 cm)

[2] S1L2 : smallest cross-sectional surface area (19.85 cm^2) and intermediate distance (14.33 cm)

[3] S1L3 : smallest cross-sectional surface area (19.85 cm^2) and longest distance (20.00 cm)

[4] S2L1 : largest cross-sectional surface area (37.97 cm^2) and smallest distance (10.05 cm)

[5] S2L2 : largest cross-sectional surface area (37.97 cm^2) and intermediate distance (14.33 cm)

[6] S2L3 : largest cross-sectional surface area (37.97 cm^2) and longest distance (20.00 cm)

Small Teflon cell: The small cell comprised a Teflon cylinder of 2.54 cm wall thickness and 2.48 cm internal radius to fit identical titanium electrodes at both ends. The cross-sectional surface area of the electrodes was 19.85 cm^2. The distance between electrodes could be varied from 10.05, 14.33 and 20.00 cm for a total volume of 200, 285 and 400 ml respectively.

Large Teflon cell: The large cell was constructed with larger diameter electrodes. A Teflon cylinder of 2.54 cm wall thickness and 3.5cm internal radius was used to fit electrodes of identical dimensions at the extremities. The cross-sectional surface area was 37.97 cm^2. The distance between electrodes could also vary (10.05, 14.33 cm and 20.00 cm) for a total sample volume of 380, 545 and 760 ml respectively.

Power Unit

A pilot scale power unit was used to perform the experiments. Details of the electrical circuit are shown in Figure 6.1b. Limits for voltage and current were 900 V and 10 A respectively. The two titanium electrodes were fitted to the extremities of the sample cylinder and connected to the power unit. Voltage and current were recorded and used to calculate the electrical conductivity. As well, temperatures at each thermocouple position were recorded at time intervals. Data were logged (Datalogger, Model Hydra 2625A, John Fluke MFG Co. Inc., Everett, WA) over a temperature range of 20-80 °C. The electrical conductivity was calculated from the resistance (R=V/I) of the sample which was converted to electrical conductivity (Palaniappan and Sastry, 1991a) with respect to the geometry of the cell (L/A), as detailed in Marcotte and Ramaswamy (1998) and Chapter 3.

Autoclave experiment

A 380 g of hydrocolloid solution sample was poured into a commercial can (size: 211x414, Ball Food and Speciality Group, Broomfield, Colorado). The diameter of the can was 6.5 cm and the length was 12 cm yielding a capacity of 385 g. A type T thermocouple was placed at the geometric centre of the can. These cans were placed in a pilot scale retort (Pilot Retort 900, Stock Inc., Germany) and heated under pasteurisation conditions to 100 °C using full immersion water cook in the static mode. Temperature profiles of the product at the geometric centre of several cans were recorded from 20°C to 80 °C. These temperature profiles were compared to time temperature profiles obtained during ohmic heating in a static cell.

Experimental design

In the first experimental protocol, three voltages (100, 250 and either 400 (20.00 cm distance) or 350 V (14.33 cm distance)) were applied to four types of hydrocolloid solutions having 0.5 % salt in the smaller Teflon cell at two electrode distances (14.33 and 20.00 cm). Therefore, six voltage gradients were obtained: 5.26, 7.14, 13.16, 17.86, 21.05 and 25 V/cm. Each experiment was performed in triplicate.

To investigate the effect of the distance between electrodes (10.05, 14.33 and 20.00 cm) and the cross-sectional surface area (19.85 and 37.97 cm^2) of electrodes simultaneously, four hydrocolloid types at 1 % salt concentration were used in the small and large Teflon cells. A constant voltage of 150 V was applied. Each experiment was performed in triplicate. Each combination of cross-sectional surface area of electrodes and distance between electrodes is listed in Table 6.1 for a total of 6: S1L1, S1L2, S1L3, S2L1, S2L2, and S2L3. S1 represents the smallest cross-sectional surface area (19.85 cm^2) and S2 the largest cross-sectional surface area (37.97 cm^2). L1 is the shortest distance (10.05 cm), L2 represents the intermediate distance (14.33 cm) and finally L3 is the greatest distance between electrodes (20.00 cm) .

Experimental heating Rate

Experimental heating rates were obtained by calculating the slopes of the curve of temperature against time, giving values of dT/dt directly at time intervals. First derivatives (dT/dt) at given t were determined using a commercial software package (TableCurve2D, Version 4, SPSS Inc., Chicago, IL).

Theoretical heating Rate

A uniform temperature non-convective system was assumed since the system involved a static unit with no particles and no flow-through circulation of the medium. Further, viscous heat dissipation was assumed to be absent. As well, radiative energy was considered negligible. The simplified thermal problem for the liquid is presented:

$$\rho_f \, C_{pf} \frac{\partial T}{\partial t} = \nabla \cdot \left(k_f \, \nabla T_f \right) + Q_f \qquad [6.1]$$

subject to the following wall boundary condition:

$$k_f \, \nabla T_f \cdot \vec{n} = U \left(T_{bf} - T_a \right) \qquad [6.2]$$

U is an overall value of heat transfer coefficient, incorporating convective and wall conductive resistances on both sides. U can be assumed to be 0 if the walls are insulated and for short duration heating conditions (<800 s). In practice, a voltage is applied to the sytem and a current will be delivered as a consequence, depending on the conductivity of the medium. Therefore, the local energy generation rate at the ohmic heater was calculated using Ohm's law:

$$\dot{Q}_f = E^2 \sigma_f = \left| V \right|^2 \sigma_f \qquad [6.3]$$

In the absence of other significant heat transfer mechanisms such as natural convection and conduction and for constant voltage conditions, the heating rate was calculated (Reznick, 1996) using the following equation:

$$\frac{dT}{dt} = \frac{\sigma_f \, E^2}{\rho_f \, C_{pf}} \qquad [6.4]$$

For the specific geometry of the experimental static ohmic heater, theoretical heating rates were calculated assuming a uniform heat generation throughout the sample and negligible heat losses to the surroundings:

$$\frac{dT}{dt} = \frac{A V^2 \sigma_f}{L M_f C_{pf}} \qquad [6.5]$$

To solve this ordinary differential equation, a FORTRAN 90 (Fortran Powerstation, Professional Edition, Version 4.0, Microsoft Corporation, Redmond, WA) program was used with the IMSL subroutine DIVPAG. The mass of fluid was estimated from the volume and density values and was found to be similar to water. The specific heat of water (4.2 kJ/kg) was used in the model. Regression equations for electrical conductivity as a function of temperature (Chapter 5) were used as input data in the model. Theoretical and experimental time-temperature profiles and heating rates were compared for all combinations of hydrocolloid type, cross-sectional surface areas of electrode and distance between electrodes.

RESULTS AND DISCUSSION

Electrical conductivity as affected by voltage gradient

Relationships between applied voltage (100, 250 and 400 V) and electrical currents generated as a consequence are shown in Figure 6.2 for all hydrocolloid types using the small Teflon cell (A: 19.85 cm^2). A fairly linear trend was found indicating that there was no deviation from Ohm's law at any temperature. It took less than 30 s for the sample to reach 80 °C from 20 °C. The slope of the these curves were constant at any temperature and is a direct measurement of the resistance (R=V/I) of the sample which is inversely related to the electrical conductivity taking into account

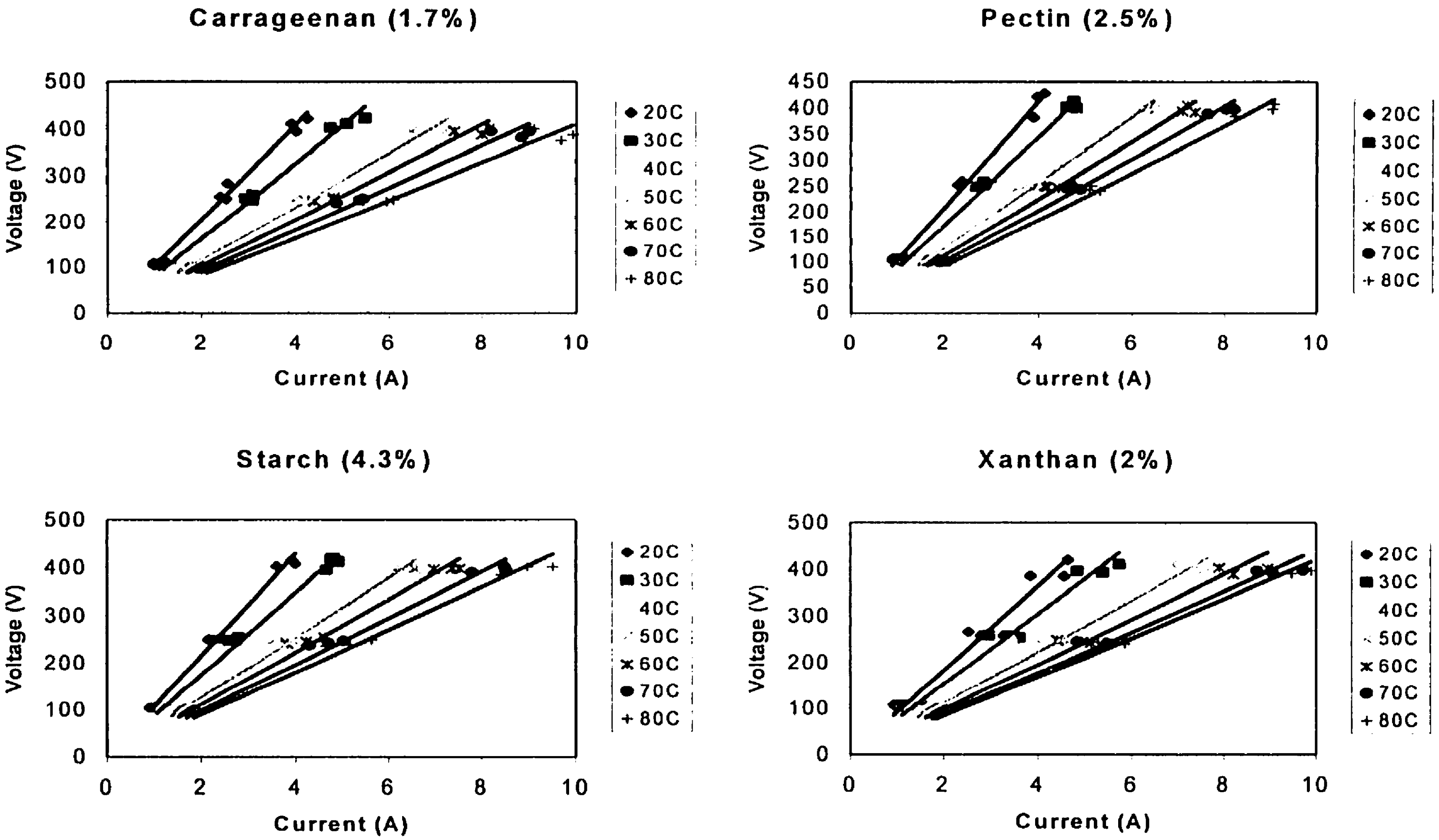


Figure 6.2 Relationships between voltage and current for selected hydrocolloid solutions at a temperature range of 20-80 °C

some geometric factors i.e. distance (L) between electrodes and cross-sectional surface area (A) of electrodes. As the temperature increased, the resistance of the sample decreased indicating higher electrical conductivities. These plots not only confirmed that Ohm's law was obeyed for all conditions but also that electrical conductivities increased with temperature, which has already been confirmed by several authors (Palaniappan and Sastry, 1991ab; Fryer *et al.*, 1993; Yongsawatdigul *et al.*, 1995b). The maximum current density was calculated as high as being 5000 A/m^2 i.e. 10 A/ 0.00198476 m^2. It was obtained at 80 °C with a current of approximately 10 A when a voltage of 400 V was applied. This would occur at the end of a typical experiment carried out at 400 V. This value never exceeded the maximum current density of 8000 A/m^2 identified by Stirling (1987) in experiments involving platinized-titanium electrodes immersed in a saturated sodium chloride solution. It is therefore assumed that there was no Faradaic current generated by electrolytic reactions. However, it should be kept in mind that the maximum current density should be maintained below 4000 A/m^2 as much as possible to minimise corrosion of the electrodes as recommended by de Alwis and Fryer (1992).

Moreover, it can be concluded also that there was no voltage gradient effect on electrical conductivities. Voltage gradients are calculated from the voltage applied divided by the distance between electrodes that was held constant during these experiments. The effect of voltage gradient has been reported for some solid foods (Halden *et al.*, 1990; Palaniappan and Sastry, 1991a; Imai *et al.*, 1995) to have a direct influence i.e. electrical conductivity increases with an increase in voltage gradient. At low voltage gradients, the electrical conductivity profile as a function of temperature has been shown to be sigmoidal instead of linear. The reason for increasing electrical conductivity with increased applied voltage, in solid food pieces, was attributed to electro-osmotic effects (Palaniappan and Sastry, 1991a) i.e. the application of voltage results in fluid motion through the capillaries of ruptured porous membranes of biological tissue causing the release of cell fluids (Halden *et al.*, 1990). Crow (1979) demonstrated that the osmotic pressure is directly proportional to the voltage gradient. This phenomenon is particular to solid foods.

Crow (1979) has reported that when applying few volts to electrolytic solutions, there is no measurable variation in electrical conductivity with voltage gradient. However, at 100 kV/cm, some differences may be observed. Palaniappan and Sastry (1991b) reported no effect of voltage gradient (30-60 V/cm) on the electrical conductivity of orange juice, a low viscosity fluid. Yongsawatdigul *et al.* (1995b) found that a high salt concentration (3-4 %) in surimi must exist to observe a voltage gradient effect on electrical conductivity. Hydrocolloid solutions are viscous and non-cellular (tissue-less) in nature and hence these arguments can support our findings i.e. independence of electrical conductivity on voltage gradient. Yongsawatdigul *et al.* (1995b) found that the dependence of electrical conductivity on voltage gradient are caused by the corrosion of electrodes at high salt concentration. Reznick (1996) stated that alternating current at low frequency such as 50 and 60 Hz has an electrolytic effect similar to that of direct current, though to a lesser extent with the major effect being the dissolution of the metallic electrode. At 100 Hz, there is no apparent dissolution of metallic electrodes. Furthermore, Stirling (1987) pointed out that Faradaic current generated by electrolytic reactions is observed when the current density exceeds 8000 A/m^2 in a platinized-titanium electrode immersed in a saturated sodium chloride solution. Yongsawatdigul *et al.* (1995b) plotted current versus voltage that should be linear if it obeys ohm's law. In the present investigation, the maximum current density employed was 5000 A/m^2 with most being less than 4000 A/m^2.

Regression equation parameters for electrical conductivity values at 0.5-1 % salt are shown in Table 6.2 for all hydrocolloid types. These were subsequently used as input data for further modelling of theoretical time/temperature profiles (discussed later). Values were found to be different only at 0.5 % salt level. In Chapter 5, it was demonstrated that a minimum of 1 % salt should be added to these solutions to overcome the difference in electrical conductivity values encountered for each hydrocolloid type. Values of σ_{25} were observed to be around 1.067-1.47 S/m with a temperature coefficient between 0.02-0.031 S/m°C. Kim *et al.* (1996a) reported a value of 1.3 S/m at 5.5 % starch which is similar to what was obtained in this experiment for starch at 4.3 % and other hydrocolloids. Yongsatwadigul *et al.* (1995b) reported a temperature coefficient of 0.03 /°C and a value of σ_{25} = 1.5 S/m for a surimi paste at 1 % salt. This temperature

Table 6.2 Regression equation parameters for electrical conductivities

Type	**Salt (%)**	**σ_{25} (S/m)**	**$K_{\sigma T}$ (S/m°C)**	**r^2**
Carrageenan (1.7%)	0.5	1.371	0.0313	0.9840
	1.0	2.173	0.0481	0.9915
Pectin (2.5%)	0.5	1.202	0.0261	0.9312
	1.0	2.195	0.0455	0.9963
Starch (4.3%)	0.5	1.066	0.0204	0.9828
	1.0	2.109	0.0427	0.9999
Xanthan (2%)	0.5	1.474	0.0305	0.9837
	1.0	2.162	0.0419	0.9747

$\sigma = \sigma_{25} + K_{\sigma T}(T-25)$

coefficient should be multiplied by σ_{25} to obtain our temperature coefficient. In doing so, a value of 0.045 S/m°C was obtained. Therefore, it can be concluded that a similar temperature coefficient is obtained for surimi paste and highly viscous solutions at 1% salt. However, the value of σ_{25} was higher for viscous fluids than for surimi paste i.e. 2.10-2.19 S/m instead of 1.5 S/m.

Time/temperature profiles as affected by voltage gradient

Figure 6.3 represents time/temperature profiles as affected by the voltage gradient for all hydrocolloid types. As the voltage gradient was increased the time/temperature profile sharpened quickly. There was a dramatic difference between 7.14 and 5.26 V/cm almost doubling the time (250 s and 500 s) to reach 80 °C. At low field strengths (10 V/cm), sample heating was relatively slow. A similar trend was observed when the voltage gradient was increased to 13.16 V/cm; there was a considerable reduction in processing time to approximately 75 s. At voltage gradients ranging from 17.86-25 V/cm, slight differences were obtained in processing time revolving around 50 s for all hydrocolloid types. There was a strong voltage gradient effect on the thermal behaviour of hydrocolloid solutions. Reznick *et al.* (1996) discussed the similar impact of voltage gradient in the design of ohmic heaters. Qihua *et al.* (1993) reported that an increase of the voltage gradient from 3.3 to 40 V/cm would result in a decrease in heating time from 5000 s to 23 s during ohmic heating of orange juice from 20 to 80 °C in a static cell. Voltage gradients were found to be linearly correlated with current densities.

Conventional time/temperature profiles generated using the autoclave, for each hydrocolloid type, are also plotted in the same Figure 6.3 for comparison purposes. It can be found that for carrageenan and pectin, the equivalent heating efficiency was found at around 7.14 V/cm. For starch, a minimum voltage gradient of 13.16 V/cm should be provided to obtain the same heating efficiency as in conventional heating. However, for xanthan, ohmic heating is particularly beneficial. Conventionally heated cans exhibited a very slow time/temperature profile. Even at the lowest voltage gradient (5.26 V/cm), the high efficiency of ohmic heating was demonstrated. This phenomenon can be explained by the viscosity effect. Xanthan solutions were found to be stable in terms of

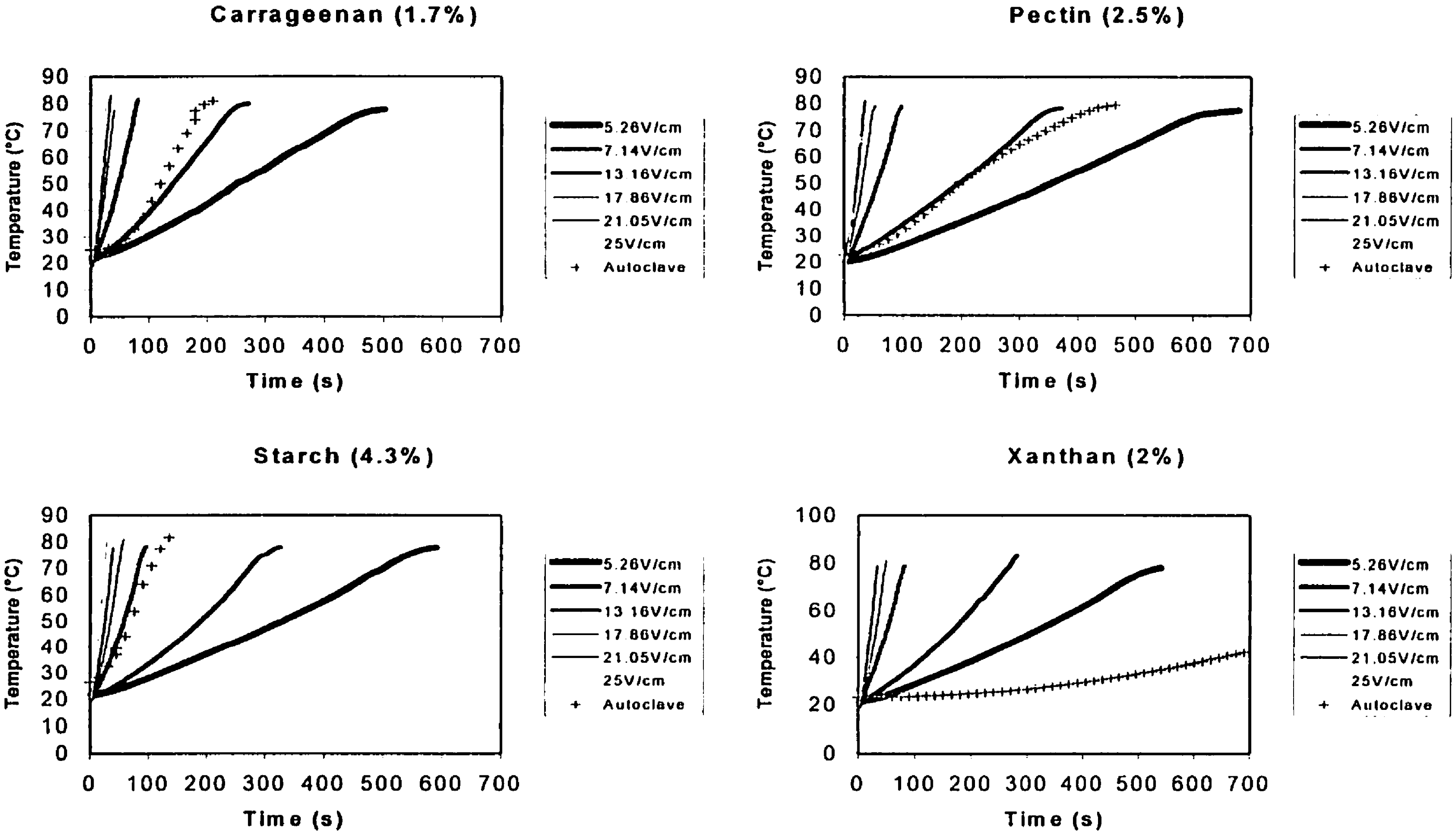


Figure 6.3 Time/temperature profiles as affected by voltage gradients

viscosity at high temperatures (Speers and Tung, 1986; Chapter 7). This is usually a desirable property to maintain in food formulations. Therefore, convection heating is minimal. It would be advantageous to heat xanthan solution with ohmic heating because not only they contain charged molecules particularly suited for ohmic heating but also because the viscosity at high temperature remains high, rendering convection heating almost useless. Thus, it can be recognised that a commercial static ohmic heating system should aim at providing a voltage gradient higher than 15 V/cm in order to obtain the considerable benefits of ohmic heating as compared to conventional heating for all hydrocolloid types, Xanthan is the exception where even the smallest voltage gradient would result in a substantial improvement in heating efficiency.

Heating rates as affected by voltage gradient and temperature

Heating rates are plotted against time in Figure 6.4 for varying voltage gradients. Higher rates were observed at higher voltage gradients. Heating rates varied from 0.05 °C/s to almost 4 °C/s depending on values of voltage gradient. Except for the two lowest voltage gradients (5.26-7.14 V/cm), heating rates increased linearly with time and consequently with temperature. This was to be expected since time/temperature profiles were concave due to the fact that electrical conductivities increase with temperature. For the lowest voltage gradient (5.26 V/cm), heating rates were rather small (0.05-0.2 °C/s). At 7.14 V/cm, heating rates were slightly higher (0.2-0.3 °C/s). Heating rates varied from 0.5 °C/s to 1 °C/s (20 to 80 °C) at 13.16 V/cm. At 17.86 V/cm, the initial heating rate was 1 °C/s at 20 °C climbing to 2 °C/s at 80 °C. This was further improved at 21.05 V/cm to 1.3 °C/s to 2.5 °C/s. Higher rates (1.6-3.6 V/cm at 20-80 °C respectively) were obtained at 25 V/cm. There were slight variations between hydrocolloid solutions. However, voltage gradients had a much greater impact on heating rates.

Heating rates were found to increase exponentially as a function of voltage gradient at different temperatures (Figure 6.5). Heating rates were also influenced strongly by temperature. At any given temperature, heating rates increased with voltage gradient, and at any given voltage gradients they increased with temperature. de Alwis *et al.* (1989) reported the effect of voltage gradient for viscous solutions on heating rates at

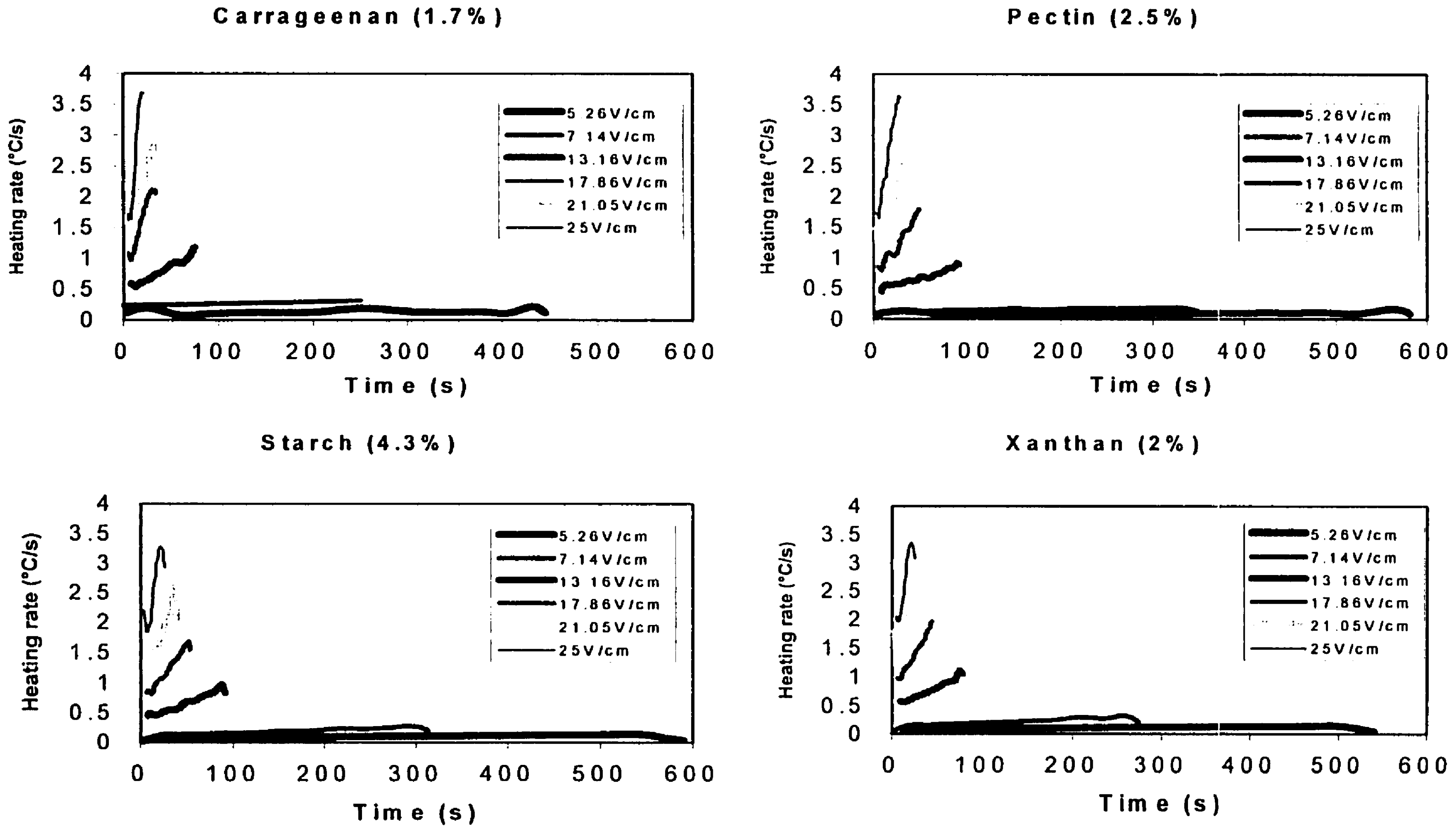


Figure 6.4 Heating rate profiles as affected by voltage gradients

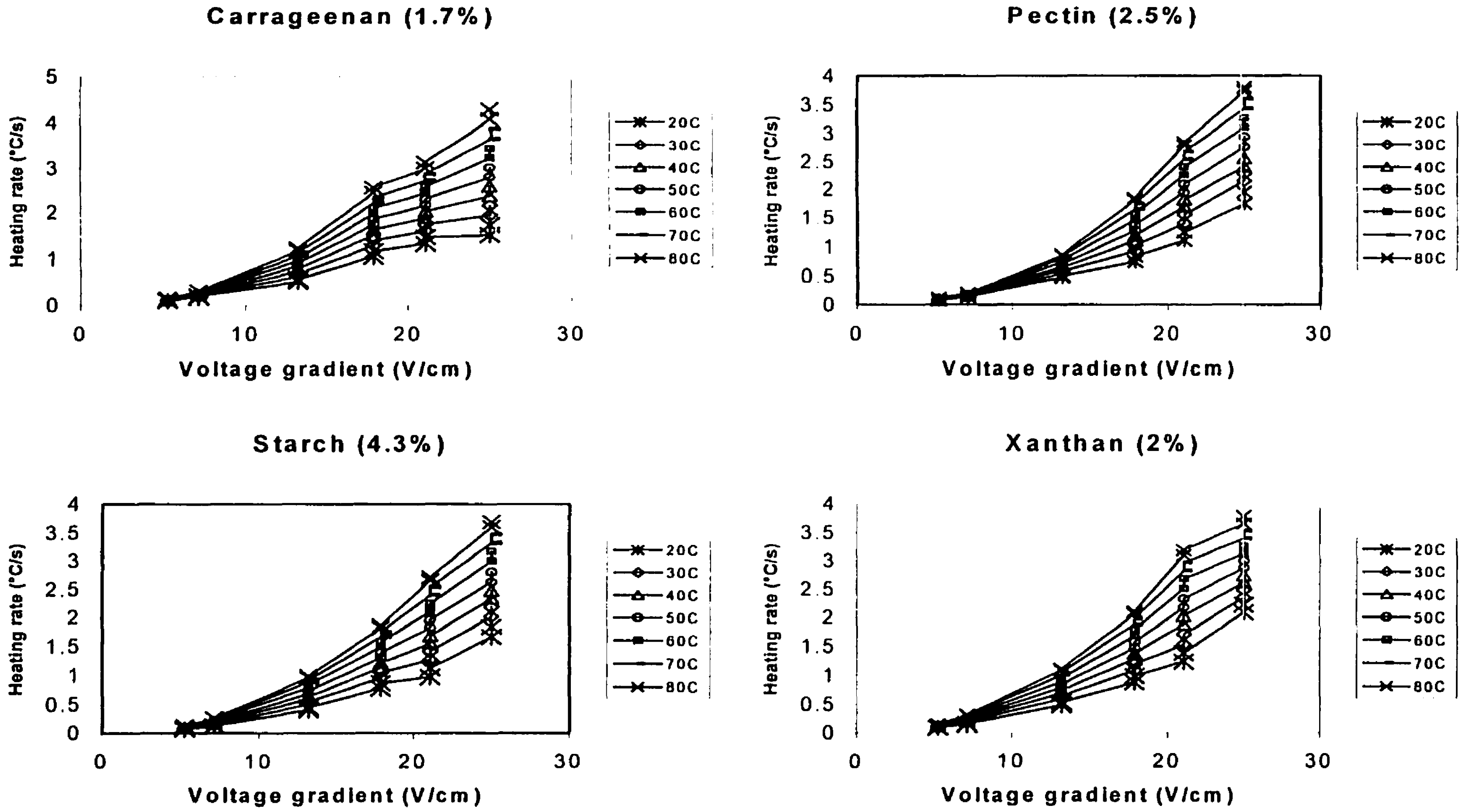


Figure 6.5 Heating rate profiles as affected by temperature

various electrical conductivity values at 20 °C. For a similar electrical conductivity, the heating rate of the viscous solution increased linearly as the voltage gradient increased from 8 V/cm to 20 V/cm. The effect was more important at 0.32 S/m, 0.42 S/m and especially at 0.9 S/m, but negligible at 0.12 S/m. In our experiments, comparable values were obtained.

Design criteria for ohmic heating

Limitations

Figure 6.6 shows current measurement against voltage for five combinations of cell configuration (i.e. distance between electrodes and cross-sectional surface area of electrodes) at all temperatures during experiments for starch at 4.3 % and 1 % salt using an initial applied voltage of 150 V. The physical limit of the power unit was 10-12 A. For some conditions (S2L1, S2L2, S2L3), a current of 10 A was attained quickly during the experiment and the voltage had to be substantially reduced to avoid blowing of the fuse. Therefore, a constant voltage situation could not be maintained during experiments. Similar ohmic heating profiles were obtained for carrageenan (1.7 %), pectin (2.5 %), and xanthan (2 %).

Assuming no configuration effect on electrical conductivity (as it was demonstrated previously that voltage gradient did not affect electrical conductivity measurements) and from the equation used to calculate the electrical conductivity value, it can be seen that if the distance is decreased by half, the current will double at any given voltage to obtain the same σ, considering that the cross-sectional surface area of electrodes is constant:

$$\sigma = \left(\frac{I}{V}\right)\left(\frac{L}{A}\right)x100 \qquad [6.6]$$

As well, if the surface area of electrodes is doubled, current values would have to double to maintain similar electrical conductivities assuming that the distance between electrodes remained constant.

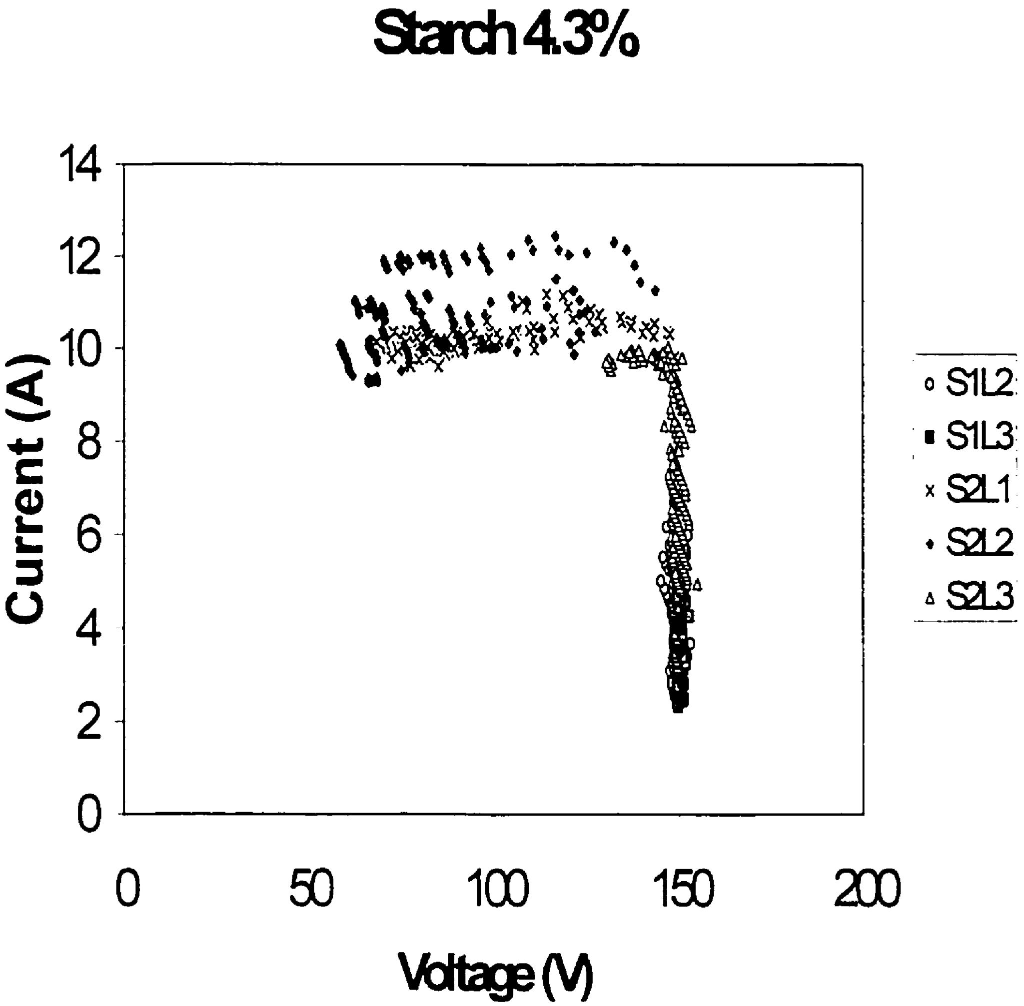


Figure 6.6 Relationships between current and voltage for five geometrical configurations of static ohmic heating cells (S1L2, S1L3, S2L1, S2L2 and S2L3) for starch (4.3 %) and 1 % salt. Surface areas (S1 and S2) are 19.85 and 37.97 cm^2. Distances (L1, L2 and L3) are 10.05, 14.33 and 20.00 cm. The initial voltage was 150 V.

The cross-sectional surface area of electrodes had a major impact on current values. For S1L2, current values were 2.79-3.14 A at 20 °C, whereas for S2L2, recorded current values were 6.00-7.14 A, at the same distance between electrodes. As well, the distance between electrodes was shown to influence current values. For a distance (L1) of 10.05 cm, currents of 10 A were attained quickly at the beginning of the experiment for the largest section (S2). The ratio between 14.33 cm to 10.05 cm is 1.43. Therefore, current values should be reduced by 1.43 to obtain 6.97 A at 20 °C. Measured values ranged from 5.91-7.14 A. Moreover, expected currents at 20.00 cm (ratio 20.00/14.327: 1.3965) would be 4.99 A. Experimental currents ranged from 4.88-5.5 A for all hydrocolloid types and L2. From this information, it can be seen that the distance between electrodes and the cross-sectional surface area of electrodes have a major impact on the static ohmic heating process. These are important geometric configuration parameters. Since currents are usually limited physically, the proper configuration should be a compromise between accelerating the heating behaviour and exceeding the limits of the power applied.

Effect of L and A on time/temperature profiles

Time/temperature profiles are presented in Figure 6.7 showing that the effect of the distance between electrodes was more important than the effect of the cross-sectional surface area of electrodes on the ohmic heating behaviour. This was expected from the theoretical Equation [6.5] that is recalled here:

$$\frac{dT}{dt} = \frac{A V^2 \sigma_f}{L M_f C_{pf}}$$

As the cross-sectional surface area (A) of electrodes is doubled, the mass of fluid (M_f) will also double. Therefore, the effect on the net heating rate (dT/dt) is zero for the same distance between electrodes. However, if only the distance is decreased by 1.43 (14.33 cm to 10.05 cm) for example, the mass of product will also decrease by the same factor. Consequently, there is a multiplication effect on heating rate that will be increased by a factor of almost 2 (1.43 x 1.43). As a result, time/temperature profiles will be sharper.

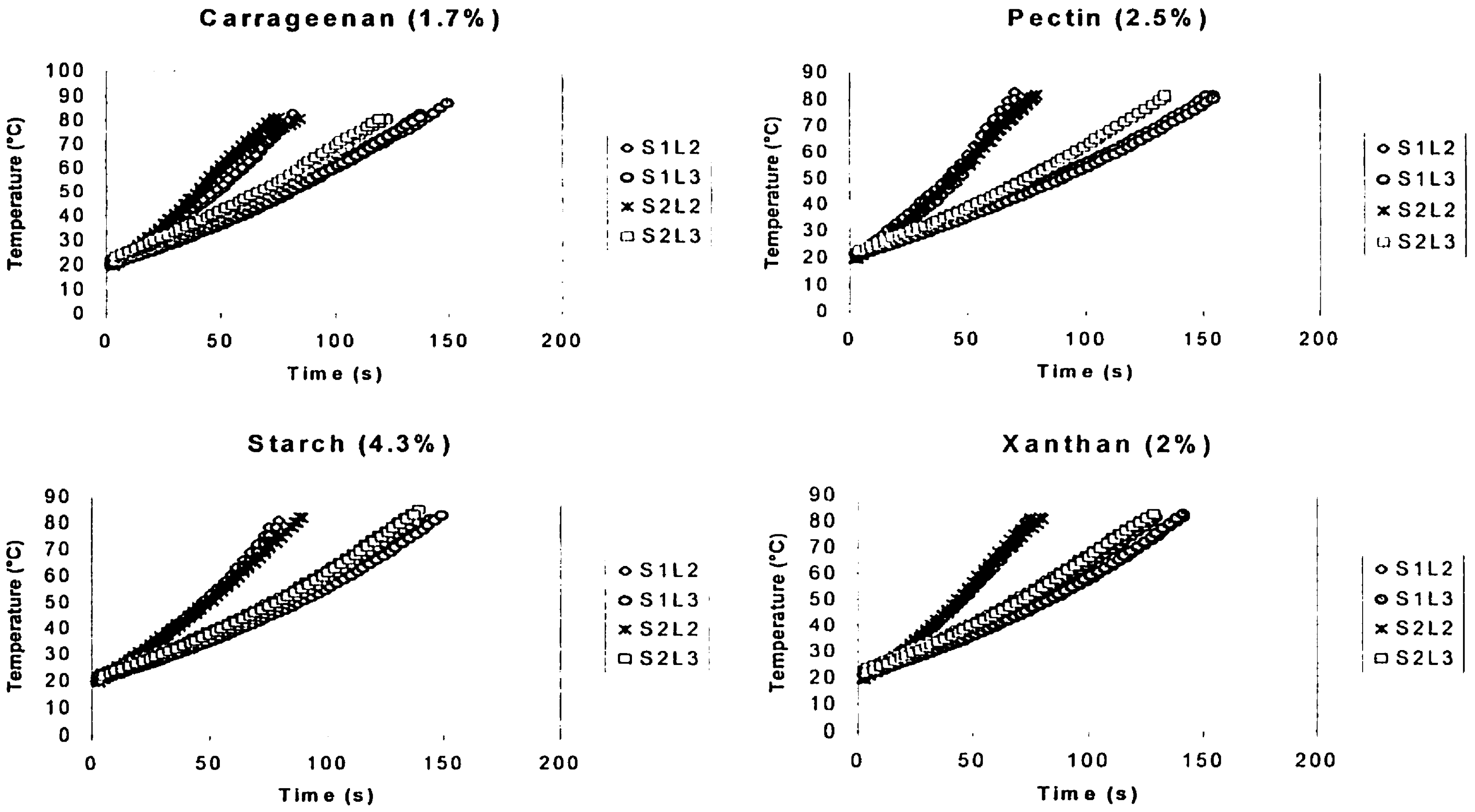


Figure 6.7 Time/temperature profiles as affected by static ohmic heating cell configurations (S1L2, S1L3, S2L2 and S2L3). Cross-sectional surface areas (S1 and S2) are 19.85 cm² and 37.97 cm² respectively. Distances (L2 and L3) are 14.33 cm and 20.00 cm. A constant voltage of 150 V is applied.

Therefore, the processing time from 20-80 °C should be reduced by half as the distance between electrodes is reduced by only 1.4. This is observed for all hydrocolloid types. The processing time was reduced from 150 s to 75 s as the distance was decreased only from 20.00 to 14.33 cm (ratio: 20.00/14.33 = 1.40). The multiplication factor was 1.95 including the mass effect. From a heating point of view in a static cell, it is preferable to reduce the distance between electrodes; this will also decrease the mass of product having a major impact on heating rates. Increasing the cross-sectional surface area of electrodes will increase the mass of product and will have no effect on heating rates.

Effect of L and A on heating rates

Heating rates are presented as a function of time in Figure 6.8. Heating rates increased with processing time and temperature which is to be expected as electrical conductivities increased with processing time and temperature. As reflected in time/temperature profiles, two groups of heating rates can be distinguished for all hydrocolloid types except carrageenan. The distance between electrodes mainly influences these data. For a distance of 20.00 cm (L3), heating rate increased linearly from 0.2 to 0.6 °C/s for all hydrocolloid types and both sections. For a distance of 14.33 cm (L2), heating rates were sharper from 0.4 to 1.2 °C/s for all hydrocolloid types. In these conditions, heating rates were similar for both sections, except for carrageenan (1.7 %) where there was an influence of the section. Small differences were observed with the cross-sectional surface area of electrodes as generally heating rates of the small section (S1) were always lower than heating rates of the larger section (S2) for a similar same distance between electrodes.

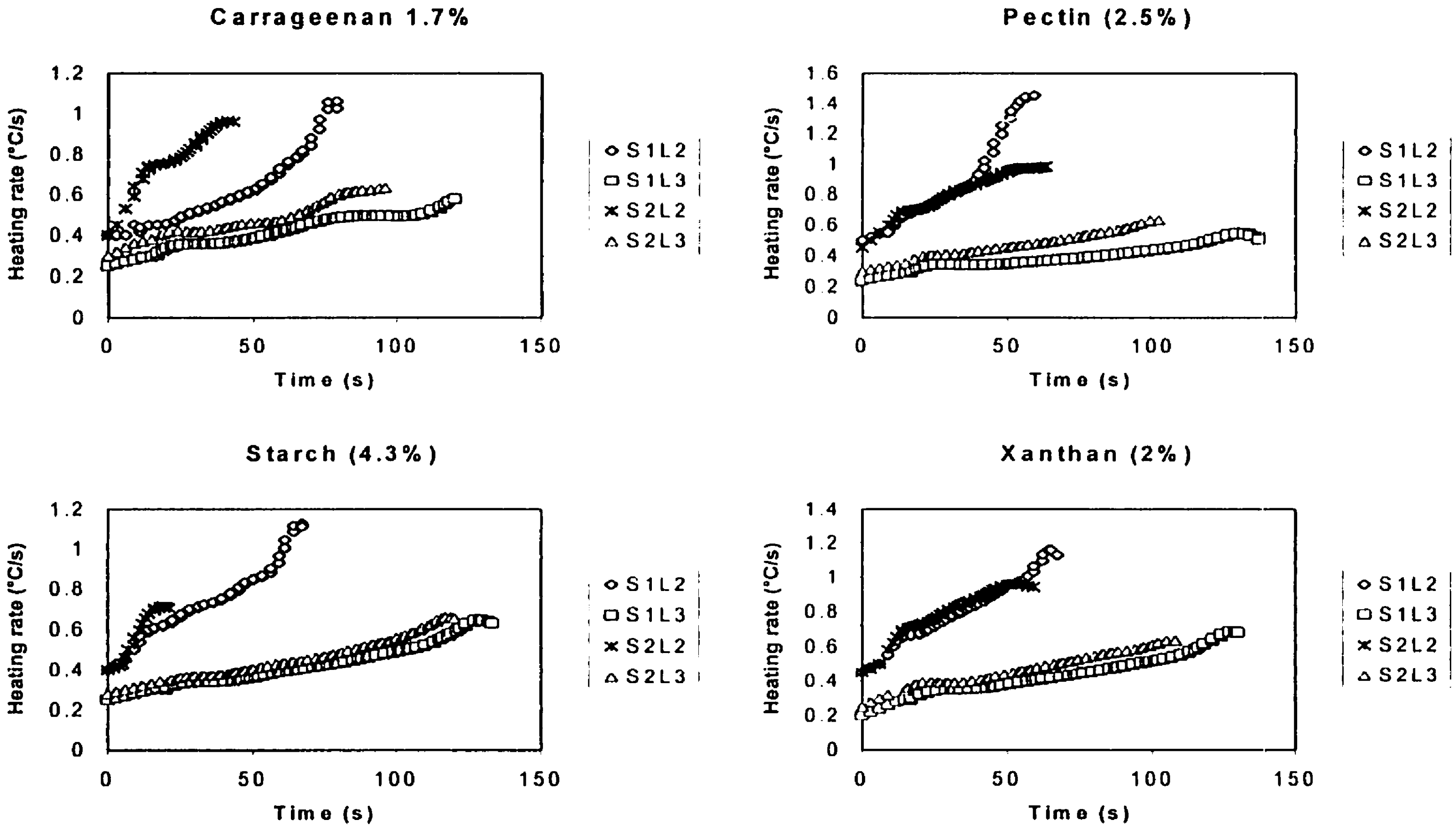


Figure 6.8 Heating rate profiles as affected by static ohmic heating cell configurations (S1L2, S1L3, S2L2 and S2L3). Cross-sectional surface areas (S1 and S2) are 19.85 cm² and 37.97 cm² respectively. Distances (L2 and L3) are 14.33 and 20.00 cm. A constant voltage of 150 V is applied.

Comparison between experimental and theoretical values

Temperature profiles

Theoretical time/temperature profiles were found to be in excellent agreement with experimental profiles for all conditions and hydrocolloid types. Current limitations prevented us from obtaining the most rapid heating rate for the smallest distance (10.05 cm). For a comparable temperature, measured processing times were plotted against calculated times in Figure 6.9 for all hydrocolloid types. It has to be pointed out that to obtain a perfect agreement between experimental and calculated times, values should lie on the diagonal. As it appears in Figure 6.9, experimental values were very close to theoretical values and these were almost on the diagonal line. A small deviation from the diagonal was found for S2L2 for all hydrocolloid types. This model could therefore be used to estimate the expected time/temperature profiles for different cell configurations.

Heating rates

Theoretical and experimental heating rates were also found to be in good agreement for all conditions as shown in Figure 6.10. Simulation values were slightly lower than experimental heating rates probably due to the fact that the specific heat of water (4.2 J/kg) was used whereas the specific heat of hydrocolloid solutions is slightly lower. Theoretical heating rates with a 10.05 cm distance between electrodes would be ranging from 1 to 2.5 °C/s even though it was impossible to realise this experiment due to the limitations of the static cells.

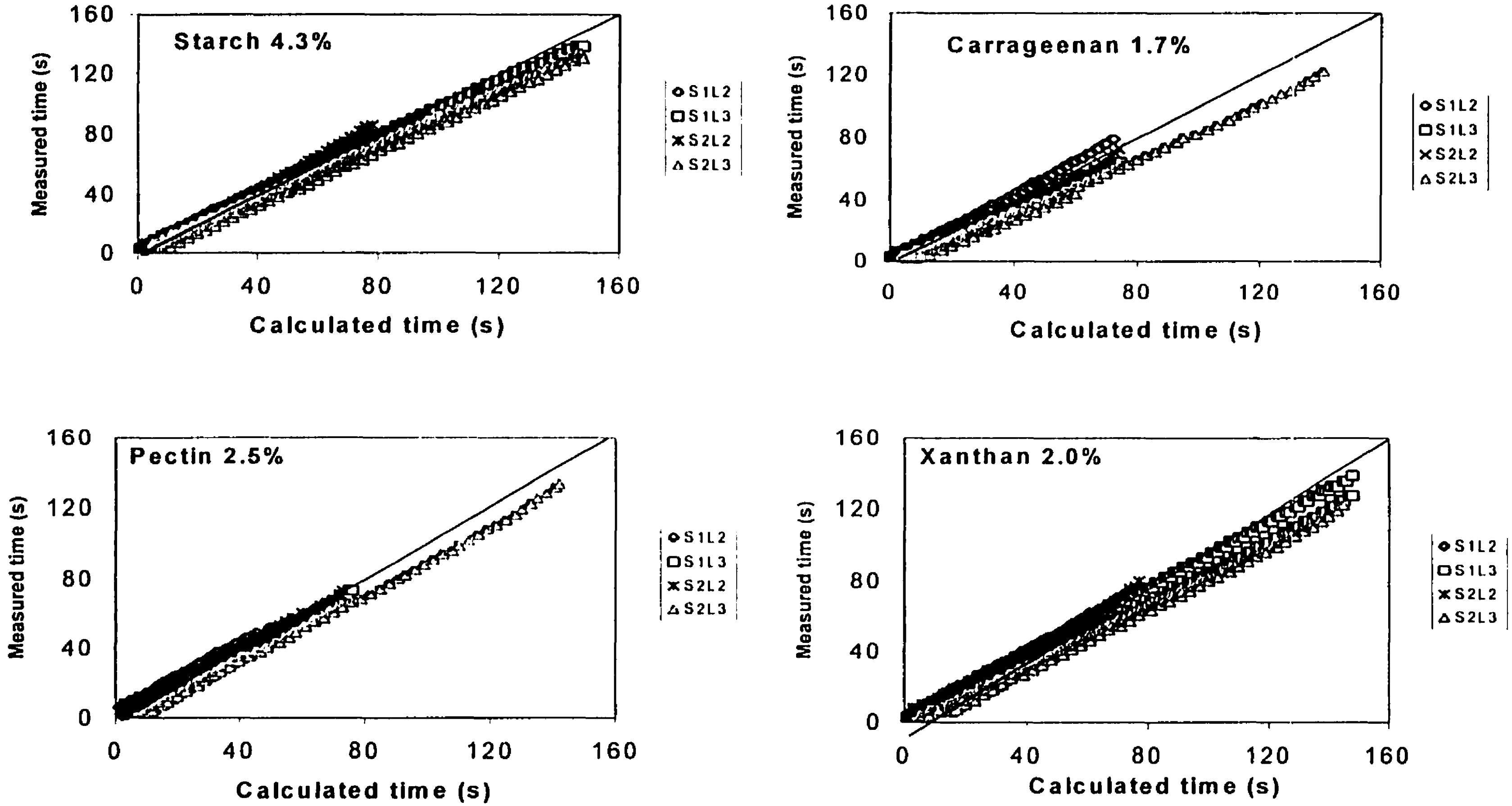


Figure 6.9 Comparison of experimental and predicted heating times to reach selected temperatures for four geometrical configurations of static ohmic heating cells (S1L2, S1L3, S2L2 and S2L3). Cross-sectional surface areas (S1 and S2) are 19.85 and 37.97 cm². Distances (L2 and L3) are 14.33 and 20.00 cm. A constant voltage of 150 V is applied.

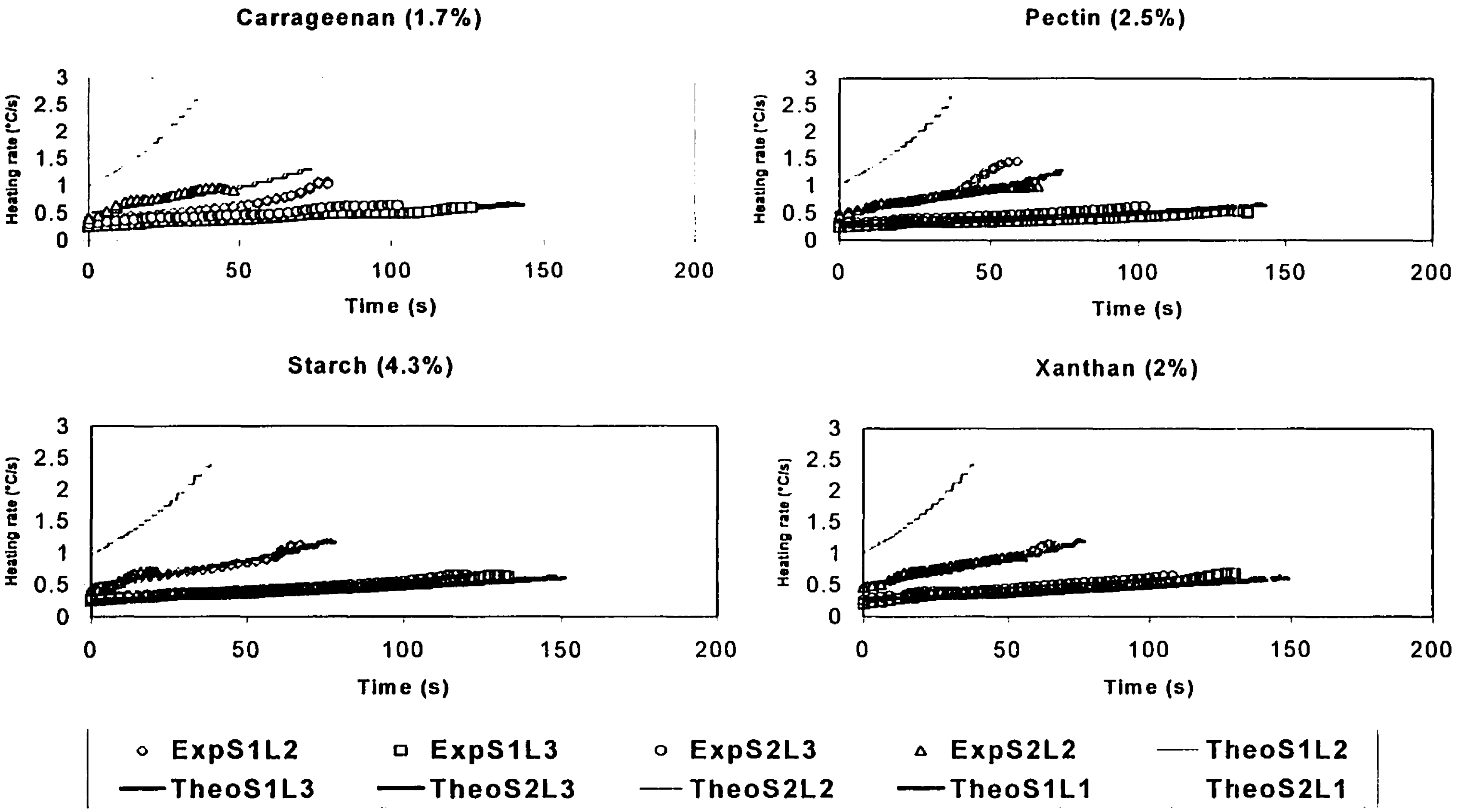


Figure 6.10 Comparison of experimental and theoretical heating rate profiles for four experimental geometrical configurations of static ohmic heating cells (S1L1, S1L2, S1L3, S2L1, S2L2 and S2L3) and two theoretical ones. Cross-sectional surface areas (S1 and S2) are 19.85 and 37.97 cm^2 respectively. Distances (L1, L2 and L3) are 10.05, 14.33 and 20.00 cm. A constant voltage of 150V is applied.

CONCLUSIONS

The results of this study indicated that there was no effect of voltage gradients on electrical conductivities but time/temperature profiles were strongly affected by this parameter. Heating rates were found to increase sharply with increasing voltage gradients. It was also shown that heating rates increased linearly with time and temperature. The distance between electrodes had a strong effect on time/temperature profiles whereas the effect of the cross-sectional surface area of electrodes was negligible. Current values, limited to 10 A, were quickly attained for specific experimental conditions. The simple mathematical model for ohmic heating of hydrocolloid solutions was in satisfactory agreement with experimental findings. Therefore, heat losses to the surroundings were negligible.

CHAPTER 7

COMPARISON OF RHEOLOGICAL PROPERTIES OF SELECTED FOOD HYDROCOLLOIDS AS A FUNCTION OF TEMPERATURE AND CONCENTRATION IN PRESENCE OF 1 % SALT

CONNECTING STATEMENT

Results from previous chapters have shown that the rheological characteristics of hydrocolloids have an effect on the uniformity of heating in static cell experiments (Chapter 4). As well, it was demonstrated that the addition of salt (1 %) overcame the effect of hydrocolloid type in these solutions as they exhibited similar electrical conductivities and heating behaviour (Chapter 5). Moreover, this salt concentration is typically encountered in particulate liquid foods (Kim *et al.*, 1996a).

Present chapter reports the results of experiments designed to characterise and compare rheological properties of selected food hydrocolloids as affected by temperature, concentration and shear rate in the presence of 1 % salt.

Results discussed in this chapter were submitted for publication to *Journal of Texture Studies* as "Rheological properties of selected food hydrocolloids as a function of shear rate, temperature and concentration in presence of 1 % salt". The authors of the manuscript are: Michèle Marcotte (Ph.D. Candidate, who planned and conducted experiments, analysed results and wrote the manuscript), Hosahalli Ramaswamy (thesis supervisor, who guided the student, revised, corrected and edited the manuscript), Ali Taherian (who assisted in analysing data) and Maher Trigui (who assisted in gathering data).

ABSTRACT

Rheological properties of hydrocolloids are important in the design, operation, and control of food processes. Addition of salt to hydrocolloids may be desirable to improve the sensory characteristics of food formulations. The purpose of this study was to characterise the flow behaviour of pectin, starch, xanthan and carrageenan solutions using a Haake RV20 rotational viscometer with an M5 OSC measuring head and a MV2 rotor at four temperatures (20, 40, 60 and 80 °C) and three concentrations. Salt was added at a 1% level for all samples. Samples were subjected to a programmed shear rate increasing from 0 to 300 s^{-1} in 3 min, held constant at 300 s^{-1} for 10 min. It was followed by a linearly decreasing shear rate to 0 during the final 3 min. Experiments were performed in duplicate. The power law model was fitted to rheograms of the shear stress/shear rate data in order to obtain the consistency coefficient (m) and the flow behaviour index (n) for starch and pectin whereas the Herschel-Bulkley (power law plastic) model was utilised for carrageenan and xanthan. Both m and n were sensitive to changes in temperature and concentration for all hydrocolloids. Deviations from Arrhenius behaviour were also found for changes in apparent viscosity at different shear rates for selected hydrocolloids.

INTRODUCTION

Thermal process design for liquid foods with or without particles require accurate information on the flow behaviour to arrive at processing conditions which ensure safety and improve quality. In these continuous processes, rheological properties play a major role in describing the heat transfer or in the design, evaluation or modelling of the continuous treatment, as flow characteristics of pumpable liquid, viscous and semi-liquid foods are dependent on fluid viscosity and density.

Hydrocolloids are commonly used as thickening agents to give product proper qualities, mostly textural characteristics. They are used in a variety of food fluids such as fruit (e.g. sauces, jams, juice concentrate etc.) or milk based products (e.g. pudding, yoghurt etc.). They may be incorporated in meat products. Furthermore, hydrocolloids in solutions need to be manipulated in various food processing unit operations, playing a major role in the transportation of solid particles in aseptic processing equipment (Palmer and Jones, 1976; McCoy *et al.*, 1987; Berry, 1989; Lee and Singh, 1991abc; 1993; Dutta and Sastry, 1990; Abdelrahim and Ramaswamy, 1995; Abdelrahim *et al.*, 1995b) including ohmic heating (Khalaf and Sastry, 1996; Kim *et al.*, 1996a) as carrier fluids for particulate foods. During ohmic heating, carrier fluids will be subjected to different shear rates in different sections in the ohmic heating process. Usually, low shear rates will be observed in straight heating tubes and high shear rates while passing through pumps.

It has been recognised that the rheological properties of hydrocolloids in solution depend on many factors: concentration of the active compound, temperature, degree of dispersion, dissolution, electrical charge, previous thermal and mechanical treatment, presence or absence of other lyophilic colloids, age of the lyophilic solution and the presence of electrolytes and non-electrolytes (Rao, 1986; Rao, 1992; Rao and Kenny, 1975). At an industrial scale, real food formulations will usually involve the addition of other ingredients. For example, Kim *et al.* (1996a) have reported that the salt content of a typical gravy or sauce of a typical particulate food, such as beef stew is between 0.6-1 %. Rheological properties of these fluids also depend on the shear rate, the duration of the shear as well as the previous shear history (Rao, 1977). As well, different temperatures are usually encountered during processing of hydrocolloids, therefore, their rheological properties should be studied as a function of temperature. For the measurement of rheological properties to be useful, a representative model should be developed. As well, a proper measurement technique should be used to cover a wide range of shear rate, temperature and concentration of hydrocolloids in solution. Finally, there should be an investigation of the time-dependency on rheological properties. Solutions of hydrocolloids are usually known to be non-Newtonian pseudoplastic fluids (Rha, 1978) which means that the apparent viscosity decreases when the shear rate is increased or that the fluid is shear thinning in nature. Several models have been used to represent the flow behaviour of gum solutions. The power law or Ostwald-de-Waele has been the most widely used model to describe the flow behaviour of solutions of hydrocolloids because of its compatibility with engineering calculations (Lalande *et al.*, 1991). Either an exponential or a power relationship (Speers and Tung, 1986) usually describes the effect of concentration on apparent viscosity. An Arrhenius type of equation (Speers and Tung, 1986) generally expresses the effect of temperature on the apparent viscosity at a specified shear rate. However, Abdelrahim *et al.* (1995b) found that it was not the best for Thermo-flo starch particularly at lower concentrations, and the combined effect of temperature and concentration on the consistency coefficient (m) and flow behaviour index (n) was evaluated by a modified Turian approach (Turian, 1964) using a multiple regression analysis. Hydrocolloid solutions may also exhibit time-dependent properties mainly thixotropy, which means that the apparent viscosity, or consistency will decrease with time. Abdelrahim *et al.* (1994) and Ramaswamy and Basak (1992) used a modified Weltmann logarithmic model to describe the thixotropic behaviour of CMC solutions and pectin in flavoured yoghurt.

The importance of salt (an ionic species) to be added to hydrocolloid solutions in order to improve the efficiency of ohmic heating was reported by Yongsatwadigul *et al.* (1995b). Typically, a food sauce would contain between 0.5-1 % salt (Kim *et al.*, 1996a). In Chapter 5, it was demonstrated that a concentration level of 1 % salt in hydrocolloid solutions overcame the effect of hydrocolloid type on electrical conductivities. Data on the rheological characteristics of carrier liquids are needed for the optimisation of the ohmic heating process. Rheological properties of some hydrocolloids were found to be affected by the salt concentration (Kelco, 1994). Therefore, 1 % salt was added to all hydrocolloid solutions in order to only study rheological properties.

The objectives of this study were: 1) to evaluate the flow behaviour of selected hydrocolloid solutions in the presence of 1 % salt, 2) to study the effect of temperature and concentration on the power law (plastic or not) parameters (m and n) and apparent viscosities of these solutions, and 3) to determine the shear rate and temperature dependency on m and n and the apparent viscosities of selected hydrocolloids.

MATERIALS AND METHODS

Preparation of solutions

Four types of hydrocolloids were studied: carrageenan (Grinsted Carrageenan, CL210, Danisco Ingredients Canada, Rexdale, ON, Canada), xanthan (Rhodigel, lot # 9635001, Rhone-Poulenc Food Ingredients, Washington, PA, USA), pectin (Grinsted Pectin, RS400 lot # 701J547, Danisco Ingredients Canada, Rexdale, ON, Canada), starch (Thermo-flo starch, NFPA 0934 lot # LF5919, National Starch and Chemical Co., Bridgewater, NJ, USA). Three levels of concentrations: carrageenan (1.5, 1.7 and 1.9 %), xanthan (1.6, 1.8 and 2.0 %), pectin (2.3, 2.5 and 2.7 %) and starch (3.8, 4.0 and 4.2 %) were selected to obtain an apparent viscosity around 0.2 Pa.s at a shear rate of 300 s^{-1} and 20 °C so that these solutions could subsequently be compared for ohmic heating behaviour at similar viscosity levels. In order to study the effect of temperature on rheological characteristics, the selected concentrations of carrageenan, xanthan, pectin and starch were 1.5 %, 2.0 %, 2.5 % and 4.0 % respectively. In each solution, 1 % salt was added as a typical concentration used in food sauces (Kim *et al.*, 1996a).

Batches of 20 l of solution were prepared in duplicate. Dry ingredients (salt and hydrocolloid powders) and water were accurately weighed. Water, placed in a double-jacketed tank, was pumped in a closed circuit. Salt was first added to the water through a butterfly valve until it was thoroughly dissolved. Then, the pre-weighed quantity of hydrocolloid powder was slowly added in the same manner and circulated to obtain a total dissolution. For carrageenan, xanthan and pectin, the solutions were then heated in the double-jacketed tank filled with hot water at 100 °C. The solution was heated until it reached 100 °C and was cooled to 20 °C. Starch solutions were heated at 140 °C after dissolution in the scraped surface heat exchanger of an aseptic system to allow for complete gelatinization.

Rheological measurement

Rheological properties of hydrocolloid solutions were evaluated using a rotational viscometer (Rotovisco, Model RV20, Haake Mess-Technik, Karlsruhe, Germany) equipped with an M5 OSC measuring head and a MV2 rotor. Solution samples were loaded into the cylindrical cup and allowed to equilibrate at a set-point temperature for 20 min in a water bath. Experiments were carried out in triplicate at four temperatures: 20, 40, 60 and 80 °C. A computer controlled program (Rheocontroller, RC20 module, Haake Mess-Technik, Karlsruhe, Germany) in a rotational mode was used to shear samples at a linear rate from 0 to 300 s^{-1} in 3 min. This was followed by a stress decay at a constant shear rate of 300 s^{-1} for 10 min and finally by a linearly decreasing shear to 0 during 3 min. Silicone oil standards (Cannon Instrument Company, State College, PA, USA) were used to calibrate the rheometer. Shear stress - shear rate data were gathered as rheograms. Apparent viscosities were calculated at 100, 200, and 300 s^{-1} in Pa.s for each combination of hydrocolloid type, concentration and temperature.

Data analysis

Flow curves or rheograms were evaluated using the power law (Equation 7.1 and 7.2) and the Herschel-Bulkley (Equation 7.3) rheological models. The effect of temperature on the consistency coefficient (m) and flow behaviour index (n) was evaluated using a modified Turian approach (Turian, 1964) through a regression analysis (Equation 7.4 and 7.5). The temperature dependency of the apparent viscosity was evaluated using an Arrhenius model (Equation 7.6). The time dependency of the shear stress was determined using the Weltmann model (Equation 7.7).

$$\tau = m\dot{\gamma}^{n} \qquad [7.1]$$

or

$$\eta_a = \frac{\tau}{\dot{\gamma}} = m\dot{\gamma}^{n-1} \qquad [7.2]$$

$$\tau - \tau_o = m\dot{\gamma}^{n} \qquad [7.3]$$

$$\log m = \log m_o - A_1 T \qquad [7.4]$$

$$n = n_o + A_2 T \qquad [7.5]$$

$$\eta_a = \eta_o \exp(-\frac{E_a}{\Re T}) \qquad [7.6]$$

$$\tau = B_1 - B_2 \log(t) \qquad [7.7]$$

RESULTS AND DISCUSSION

Characterisation of flow curves

The typical flow behaviour of selected hydrocolloids at a constant temperature of 20 °C under dynamic and steady shearing is presented in Figure 7.1. The curves of all samples showed a shear thinning behaviour ($n < 1$) with a yield stress for xanthan and carrageenan. A yield stress for carrageenan solutions was observed only at 20 and 40 °C, while curves of xanthan exhibited large yield stress values at all temperatures. It should be noted that a stress decay at a steady shear rate was observed for carrageenan solutions at lower temperatures (20 and 40 °C) only. The intercept value (B_1) and the slope (B_2), based on the Weltmann model (Weltmann, 1943), were found to be 96.8 and 26.3 at 20 °C and 15.9 and 3.3 at 40 °C for carrageenan. There was no yield stress for starch and pectin solutions at any test temperature. The yield value, or "the shear stress that must be exceeded before the flow can begin", is consistent with the pseudoplastic behaviour and particular suspensoid property of xanthan solutions over a wide range of temperatures. For instance, xanthan gum was reported to increase the stability of mayonnaise and emulsion (Hibberd *et al.*, 1987) as well as its structure by the formation of larger size aggregates (Yilmazer and Kokini, 1992).

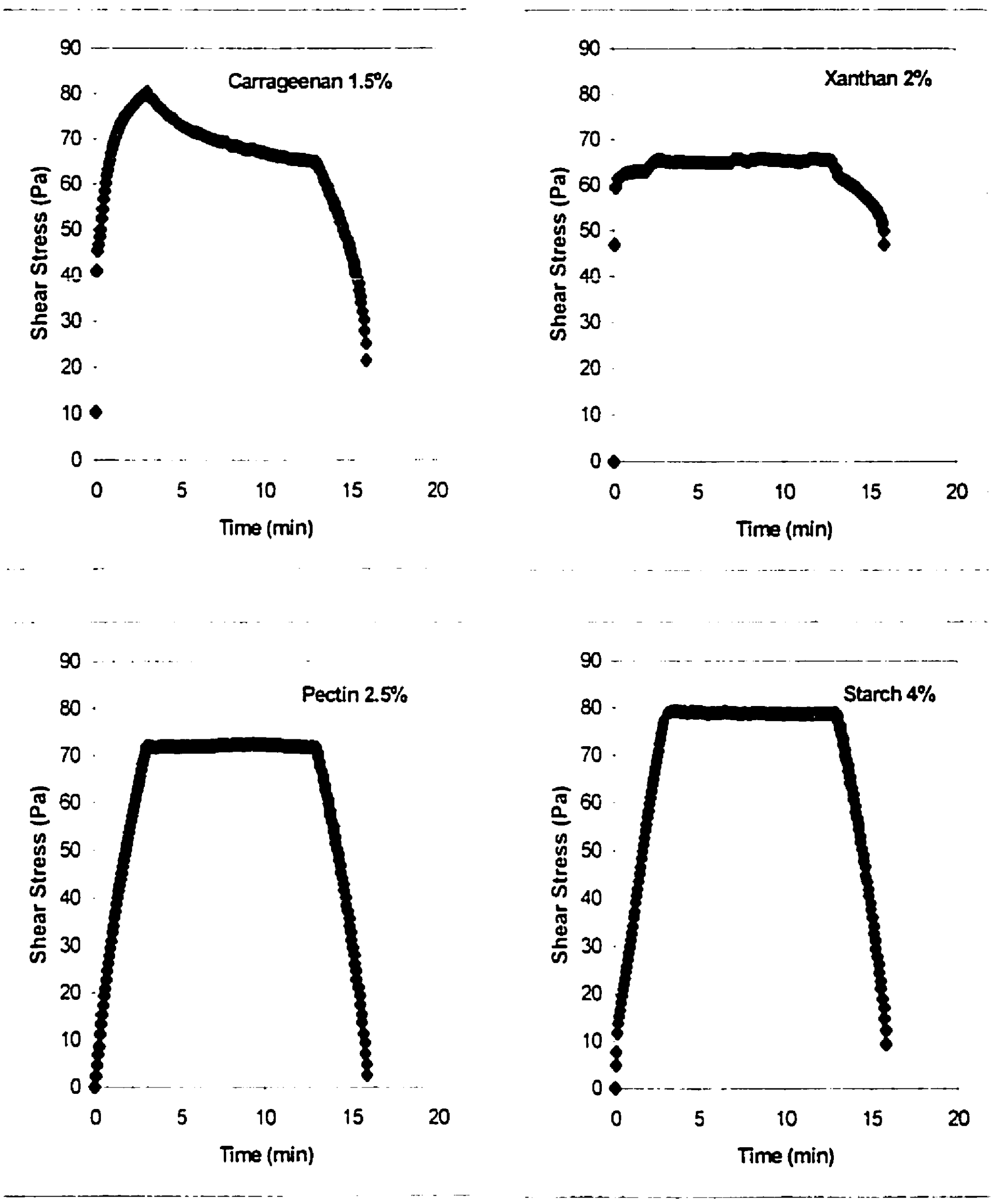


Figure 7.1 Typical flow behaviour of selected hydrocolloids at 20 °C

Rheological models and effect of temperature on flow parameters

The power law model was applied to characterise the flow behaviour of pectin and starch, while the flow behaviour of xanthan and carrageenan, which denoted the yield stresses (power law plastic model), was described by the Herschel-Bulkley model for both upward and downward curves. Table 7.1 and 7.2 show the means and standard deviations of the power law and Herschel-Bulkley parameters associated with selected hydrocolloids at the mid concentration levels. Obtained high values of coefficient of determination (r^2) indicated a good fit for both models for each hydrocolloid. There was a decrease in the consistency coefficient with the increasing temperature related to the flow and the texture of hydrocolloids. Coefficients of variation were calculated and for most cases were less than 5 %, with few exceptions not exceeding 15 %. The Turian approach showed a decrease in consistency coefficient at higher temperatures with an increase in flow behaviour index (Figure 7.2 and Figure 7.3) for all hydrocolloids. Values of Turian parameters are tabulated in Table 7.3.

Temperature dependency of apparent viscosity

The effect of temperature on the viscosity of hydrocolloids must also be known in ohmic heating, as they will be subjected to a range of temperatures. The Arrhenius relationship has been used by many researchers (Ramaswamy and Basak, 1991; Rao and Anantheswaran, 1982; Hernandez *et al.* 1995) to describe the temperature dependency of rheological parameters. In this study, the Arrhenius approach was used to compare the changes in apparent viscosity of selected hydrocolloids at different temperatures (Figure 7.4).

There was a minor temperature influence for xanthan and accordingly the lowest activation energies (E_a at 100 s^{-1} = 1.75 kJ/mole and r^2 = 0.97, E_a at 200 s^{-1} = 1.33 kJ/mole and r^2 = 0.95, and E_a at 300 s^{-1} = 1.08 kJ/mole and r^2 = 0.92) were obtained. The apparent viscosity of xanthan was mostly affected by shear rate. As mentioned earlier, xanthan was the only hydrocolloid, which exhibited a significant yield stress for all measuring temperatures. This means that xanthan solutions have the ability to retain

Table 7.1 The power law parameters for pectin (2.5 %) and starch (4 %) at selected temperatures

	Upward Curve			Downward Curve		
	n	m	r^2	n	m	r^2
20 °C						
Pectin	0.827±0.004	0.68±0.01	0.99	0.82±0.02	0.68±0.10	0.99
Starch	0.516±0.006	1.84±0.02	0.99	0.59±0.004	1.58±0.02	0.99
40 °C						
Pectin	0.851±0.019	0.32±0.03	0.99	0.893±0.01	0.26±0.02	0.99
Starch	0.531±0.003	1.46±0.08	0.98	0.60±0.009	1.24±0.11	0.99
60 °C						
Pectin	0.913±0.012	0.13±0.005	0.98	0.95±0.01	0.106±0.01	0.99
Starch	0.558±0.011	1.03±0.07	0.99	0.63±0.01	0.82±0.05	0.99
80 °C						
Pectin	0.92±0.01	0.06±0.003	0.97	0.99±0.015	0.03±0.004	0.99
Starch	0.585±0.02	0.61±0.014	0.98	0.65±0.01	0.65±0.07	0.99

Table 7.2 The Herschel-Bulkley parameters for xanthan (2 %) and carrageenan (1.5 %) at selected temperatures

		Upward Curve			Downward Curve		
	τ_0	n	m	r^2	n	m	r^2
20 °C							
Xanthan	36	0.247±0.005	7.52±0.67	0.95	0.22±0.02	7.14±1.10	0.99
Carrageenan	35	0.332±0.02	7.64±0.21	0.97	0.74±0.04	0.29±0.009	0.99
40 °C							
Xanthan	30	0.259±0.02	6.75±0.08	0.99	0.26±0.01	5.77±0.13	0.99
Carrageenan	4.5	0.338±0.01	1.99±0.04	0.98	0.76±0.05	0.06±0.004	0.99
60 °C							
Xanthan	28	0.275±0.004	5.90±0.08	0.99	0.35±0.03	4.75±0.02	0.99
Carrageenan	0.03	0.874±0.009	0.02±0.002	0.98	0.94±0.02	0.01±0.001	0.99
80 °C							
Xanthan	23	0.288±0.02	5.56±0.08	0.98	0.37±0.01	4.54±0.16	0.99
Carrageenan	0.02	0.879±0.02	0.02±0.002	0.92	0.98±0.01	0.008±0.0007	0.99

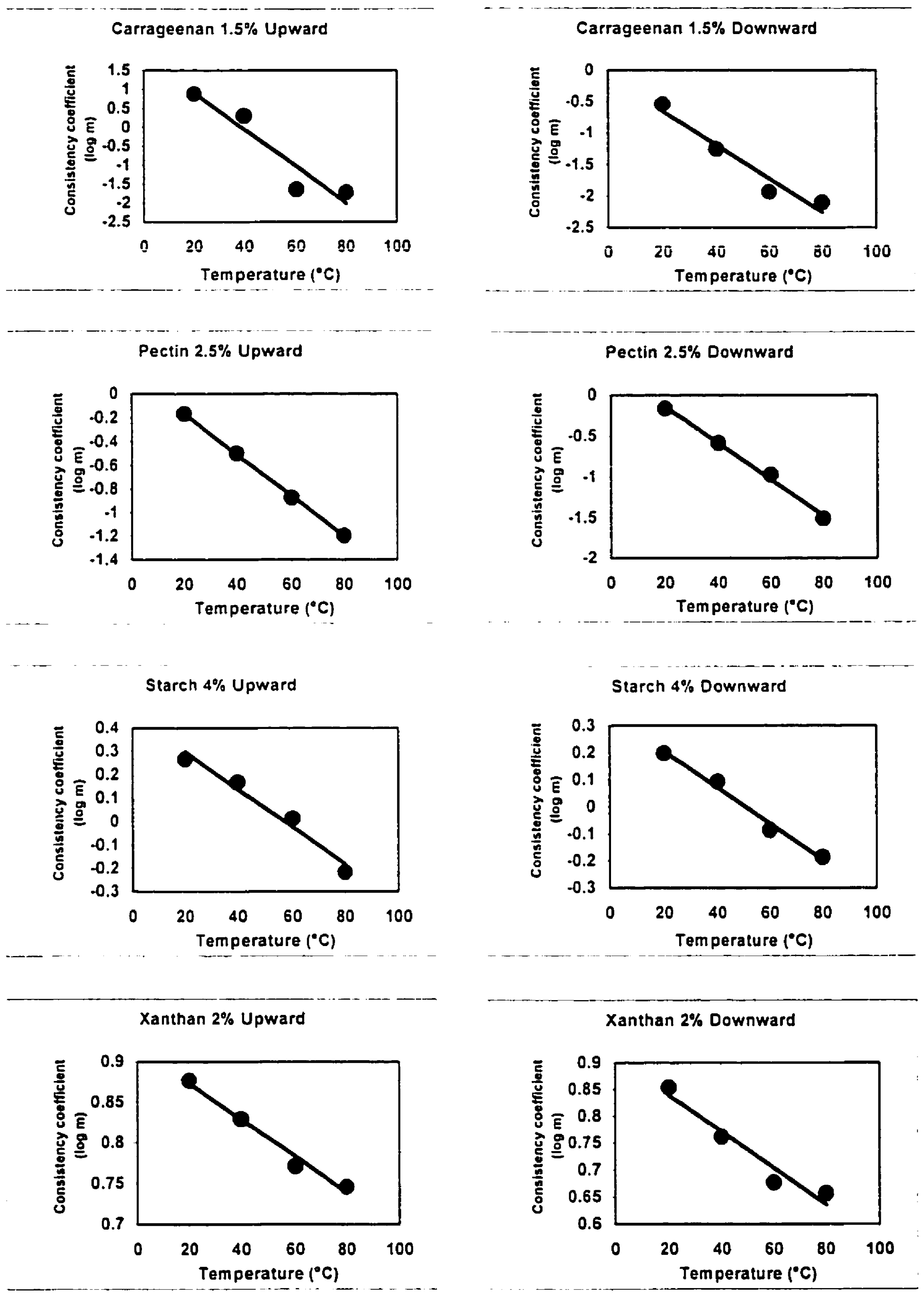


Figure 7.2 Effect of temperature on consistency coefficient (m) of hydrocolloid solutions using the Turian approach

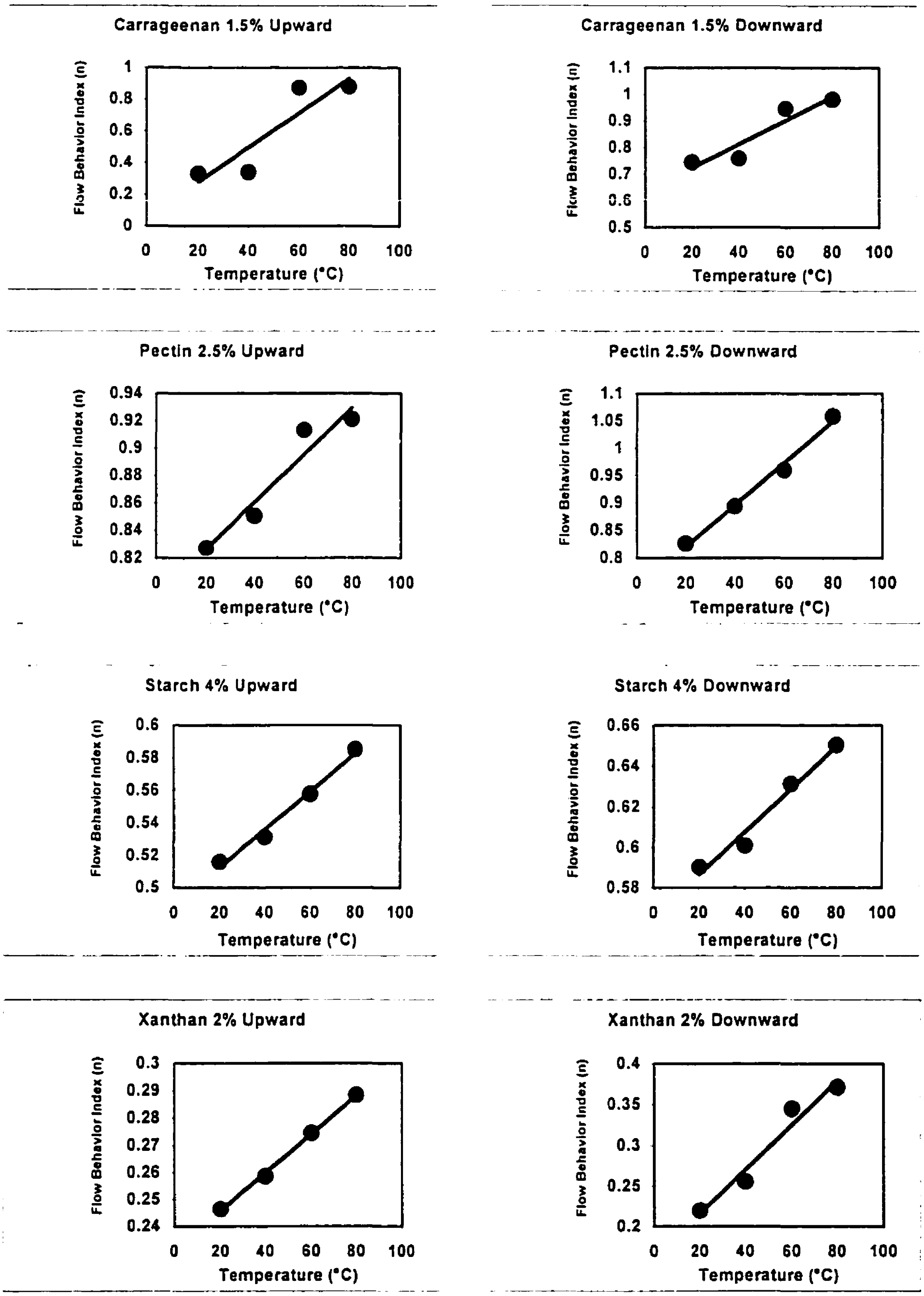


Figure 7.3 Effect of temperature on flow behaviour index (n) of hydrocolloid solutions using the Turian approach

Table 7.3 The Turian parameters for selected hydrocolloids

Sample	Log m_o	A_1	n_o	A_2
Carrageenan (1.5%)				
Upward	1.89	-0.049	0.06	0.0108
Downward	-0.12	-0.027	0.63	0.0044
Pectin (2.5%)				
Upward	0.18	-0.017	0.79	0.0017
Downward	0.30	-0.022	0.74	0.0038
Starch (4%)				
Upward	0.46	-0.008	0.49	0.0012
Downward	0.34	-0.007	0.57	0.0011
Xanthan (2%)				
Upward	0.92	-0.002	0.23	0.0007
Downward	0.91	-0.003	0.16	0.0027

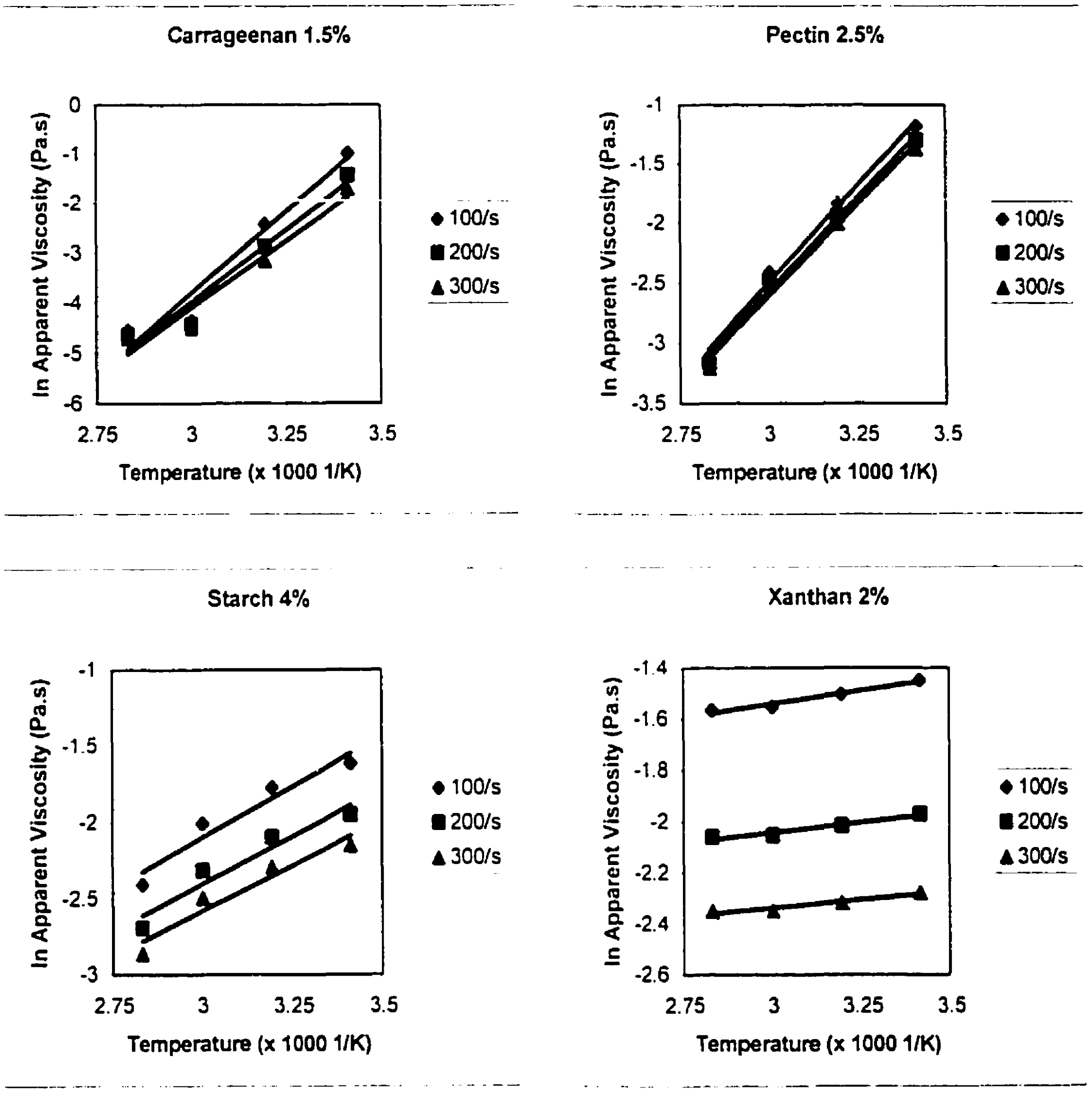


Figure 7.4 Arrhenius plots for selected hydrocolloids.

their gel network and viscosity at higher temperatures. An investigation (Kelco, 1994) also showed that xanthan gum solutions maintain their viscosities until a specific "melting temperature" is reached. Their data showed that the melting temperature in presence of 0.5 % salt is greater than 80 °C and an addition of salt concentration (up to 5 %) increases the melting temperature to over 110 °C. A structural study by Sanderson (1981) showed that xanthan exhibited the viscosity stability at elevated temperatures, high at-rest or low-shear viscosity accompanied with yield value as a result of weak intermolecular associations, even at very low gum concentration and high pesudoplasticity. This results from the progressive alignment of the rigid molecules with the shearing force.

Carrageenan solutions, which only denoted the yield stresses at 20 and 40 °C, showed the highest level of activation energies indicating a lower resistance at elevated temperatures. Activation energies ranged from 55 kJ/mole with $r^2 = 0.95$, 49 kJ/mole with $r^2 = 0.95$ and 45 kJ/mole with $r^2 = 0.95$ at 100, 200 and 300 s^{-1} respectively. Pectin showed lower temperature sensitivity than carrageenan but higher than xanthan. Activation energies for pectin were 27 kJ/mole with $r^2 = 0.99$ at 100 s^{-1}, 26 kJ/mole with $r^2 = 0.99$ at 200 s^{-1} and 26 kJ/mole with $r^2 = 0.99$ at 300 s^{-1}. The activation energy values for starch were lower than pectin solutions, ranging from 11, 10, and 9.9 kJ/mole with $r^2 = 0.93$ at 100, 200 and 300 s^{-1} respectively. It should be noted that a decrease in activation energy is always associated with an increase in the shear rate.

Effect of concentration on flow parameters

The relationship between rheological parameters, evaluated at 20 °C, and concentration is shown in Table 7.4. The power law model described the upward and downward curves for starch and pectin and the Herschel-Bulkley model was used to characterise the flow behaviour for xanthan and carrageenan. It is evident that the concentration had a considerable effect on the flow behaviour of hydrocolloid solutions. All samples at lower concentration displayed a lower consistency coefficient (m) and an

Table 7.4 **Effect of concentration on upward and downward curves for selected hydrocolloids at 20 °C**

		Upward Curve			Downward Curve		
	τ_o	n	m	r^2	n	m	r^2
Xanthan*							
1.6%	29	0.276±0.004	3.46±0.06	0.98	0.41±0.01	2.93±0.15	0.99
1.8%	33	0.259±0.007	5.35±0.19	0.97	0.34±0.01	3.31±0.13	0.99
2%	36	0.241±0.003	7.26±0.12	0.98	0.33±0.007	4.05±0.09	0.99
Carrageenan*							
1.5%	33	0.338±0.010	7.69±0.18	0.97	0.81±0.03	0.28±0.02	0.99
1.7%	45	0.327±0.008	15.3±0.29	0.95	0.69±0.01	1.17±0.10	0.99
1.9%	48	0.281±0.008	21.3±0.94	0.99	0.60±0.008	2.03±0.08	0.99
Starch**							
3.8%	-	0.600±0.013	1.04±0.03	0.99	0.64±0.02	1.18±0.06	0.99
4%	-	0.514±0.021	1.89±0.08	0.98	0.62±0.01	1.51±0.04	0.99
4.2%	-	0.494±0.026	2.72±0.27	0.98	0.58±0.03	2.11±0.14	0.99
Pectin**							
2.3%	-	0.820±0.015	0.56±0.06	0.99	0.83±0.02	0.52±0.04	0.99
2.5%	-	0.821±0.007	0.71±0.04	0.99	0.82±0.02	0.73±0.09	0.99
2.7%	-	0.823±0.005	0.81±0.04	0.99	0.79±0.007	0.93±0.07	0.99

* Herschel Bulkley model
** Power law model

increase in concentration was accompanied with a progressive upward shifting of the curve. The apparent viscosity (η_a) depended on both m and n within the concentration ranges studied: the flow behaviour indexes were only marginally different and did not show any specific trend. However, a shear thinning behaviour was observed for all selected hydrocolloids. Similar trends were observed with the downward curves.

Effect of concentration and shear rate on apparent viscosity

The effect of shear rate and concentration at 20 °C on apparent viscosity, calculated as the ratio of shear stress to shear rate, is shown in Figure 7.5. It should be noted that each curve represents the mean of six measurements (two separate batches x three rheological measurement) using the power law and Herschel-Bulkley models to express the results. As expected, the viscosity of all samples increased with increasing concentration.

The concentration effect was quite dominant for carrageenan solution and showed an 88 % and 112 % increase in apparent viscosity, as the concentration was increased from 1.5 to 1.7 and 1.9 % respectively. Xanthan was less affected by concentration and displayed a 43 % and 79 % increase in apparent viscosity, as the concentration changed from 1.6 to 1.8 and 2 %. The apparent viscosity of pectin increased by 20 % and 39 % as the concentration increased from 2.3 to 2.5 and 2.7 %. As compared to other hydrocolloids, starch showed an intermediate behaviour as a function of concentration. Apparent viscosities were increased by 22 and 59 % as concentration increased from 3.8 to 4 and 4.2 %.

Increasing the shear rate from 100 s^{-1} to 200 s^{-1} and 300 s^{-1} resulted in a decrease of apparent viscosity of carrageenan by 37 % and 52 %. Xanthan was mostly affected by the shear rate and showed a 39 % and 55 % reduction in apparent viscosity as the shear rate increased from 100 s^{-1} to 200 s^{-1} and 300 s^{-1}. When increasing shear rate up to 200 s^{-1} and 300 s^{-1} for pectin, the apparent viscosity of pectin decreased by 11 % and 17 %.

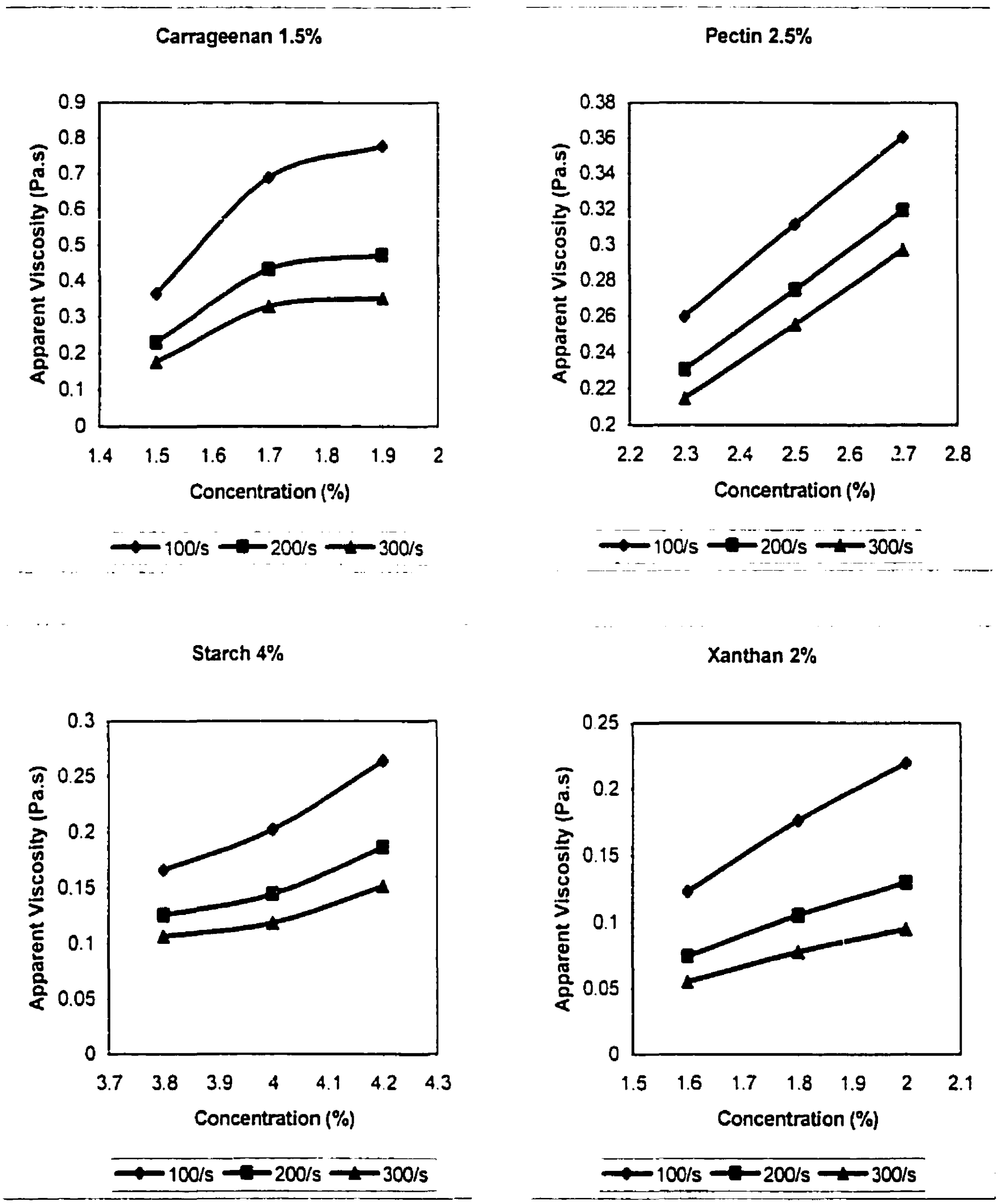


Figure 7.5 Effect of concentration and shear rate on apparent viscosity

For starch, shifting the shear rate from 100 s^{-1} to 200 s^{-1} and 300 s^{-1} resulted in loss of 24 % and 36 % in apparent viscosities.

CONCLUSIONS

A shear thinning behaviour was observed for all selected hydrocolloids for upward and downward rheograms. Temperature, concentration and shear rate effects on rheological properties were different depending on the type of hydrocolloids. Flow curves were well described by the power law model for starch and pectin. Yield stresses were observed for carrageenan at 20 and 40 °C only and for xanthan at all temperatures. For these, Herschel-Bulkley models were appropriate. The temperature dependency of m and n was modelled using a modified Turian approach. Both the consistency coefficient (m) and the flow behaviour index (n) were sensitive to changes in temperature and concentration. As the temperature of the solution increased, m decreased and n increased. As the concentration of the solution was increased, m increased and n decreased.

The concentration effect on the apparent viscosity was more important for starch and carrageenan and less for pectin and xanthan. It was quite dominant for carrageenan solutions. Xanthan was less affected by concentration but mostly by the shear rate. Carrageenan solutions showed the highest level of activation energy indicating a lower resistance to decrease the apparent viscosity at elevated temperatures. Pectin resulted in a lower temperature sensitivity of the apparent viscosity than carrageenan and higher than xanthan.

A time dependency was found only for carrageenan and a modified Weltmann model was used to evaluate the effect of time on the shear stress.

CHAPTER 8

MATHEMATICAL MODELLING OF FLOW AND THERMAL BEHAVIOUR OF HYDROCOLLOID SOLUTIONS DURING OHMIC HEATING IN A CONTINUOUS UNIT

CONNECTING STATEMENT

In previous chapters, data have been generated on electrical conductivities of hydrocolloid solutions with varying salt concentrations (0.25-1 %) (chapter 5) and temperatures. As well, the rheological properties were determined for all selected hydrocolloids in presence of 1 % salt as a function of temperature (chapter 7). These results for 4 % starch can be as input data for modelling purposes.

In chapter 8, a theoretical model describing the flow and the thermal behaviour of a solution of starch at 4 % with 1 % salt in a continuous ohmic heating is developed and tested. Experimental measurements are performed to measure the temperature distribution within the continuous ohmic heating column that will be used to validate the model.

The content of the chapter 8 is currently being prepared and will be sent for publication as « Mathematical modelling of flow and thermal behaviour of hydrocolloid solutions during ohmic heating in a continuous unit » to the *Journal of Food Engineering*. The authors are: Michèle Marcotte (Ph.D. Candidate, who planned and conducted experiments, analysed results and wrote the manuscript), Hosahalli Ramaswamy (thesis supervisor, who guided the student and corrected, edited and revised the manuscript) and Maher Trigui (who assisted in the development of the model and gathering data).

ABSTRACT

A theoretical model describing the flow and the thermal behaviour of hydrocolloid solutions in a continuous ohmic heating unit was developed solving simultaneously the equations of Laplace, Fourier and Navier-Stokes, including temperature dependent electrical and thermal conductivities and viscosities, with a commercial computational fluid dynamics software package (FIDAP). The model was validated experimentally for starch at 4 % in the presence of 1 % salt, a non-Newtonian liquid. Experimental data generated for electrical conductivity, rheological property, thermal conductivity, density and specific heat and their temperature dependency were evaluated and subsequently used as inputs to test the model. Experiments were performed in the continuous ohmic heating unit. Temperature profiles were recorded at time intervals and along the geometry of the ohmic heating column until it reached steady state. Theoretical temperature profiles were compared to experimental data and found in good agreement.

INTRODUCTION

Industrial ohmic heaters are engineered to interface with a continuous process line. A full model of ohmic heating for viscous liquids requires the simultaneous solution of the flow, electrical and thermal differential equation in the geometry of the heater.

Most published models have tried to describe the thermal behaviour of particles in a still liquid. In this case, the conduction heat transfer equation and a temperature dependent internal energy generation govern the heat transfer for particles with a time-dependent boundary condition at the surface of the particle and uniform initial conditions. Electric and thermal partial differential equations (PDE) were coupled and solved for the geometry of the heater. Relevant assumptions in solving the PDE were often made such as constant thermal properties, homogeneous and isotropic particle, pure conduction heating within the particle and no phase change in the fluid and particle during processing. Specifically, models were developed for ohmic heating of solid-liquid mixtures that have been validated experimentally for a single particle in a static heater (de

Alwis and Fryer, 1988; de Alwis *et al.*, 1989; de Alwis and Fryer, 1990b; de Alwis and Fryer, 1990c; de Alwis and Fryer, 1992; Fryer *et al.*, 1993; Sastry and Palaniappan, 1992b; Zaror *et al.*, 1993). Analytical solutions were often used to verify the model.

For multiple particle systems in static ohmic heaters, simplified models have been presented for a limited number of particles (Sastry and Palaniappan, 1992c; Sastry and Li, 1993; Zhang and Fryer, 1993; Zhang and Fryer, 1995).

Two different approaches have been used for the calculation of the electric field within the system. De Alwis and Fryer (1990b) reported that the electric field, in which the electrical conductivity varies with position, could be modelled by solving the Laplace equation with appropriate boundary conditions. Using this approach, computer simulations were found to be time consuming. Therefore, this approach could only be used to solve simple system of one particle involving no convection for the liquid. A circuit analogy approach was suggested by Sastry and Palaniappan (1992c) for the solution of the electric field where the ohmic heater was considered to be a set of equivalent resistances. For a static ohmic heater, results of both methods were compared in two papers (Zhang and Fryer, 1995; Sastry and Salengke, 1998) for one particle immersed in a still liquid. The two approaches gave similar results for mixtures of solids content greater than 30%. Discrepancies were found at low solids concentration. The Laplace equation no convection method (Fryer's group) was more conservative for the inclusion of higher electrical conductivity particle than the fluid. But, the circuit analogy mixed fluid (Sastry's group) method predicted a more conservative temperature profilefor the inclusion of low electrical conductivity particles with respect to the fluid.

Fryer *et al.* (1993) studied the ohmic heating of the liquid phase in an heterogeneous mixture for a static heater. In order to understand the thermal behaviour of the liquid phase, two simple limiting cases of an infinite linear field around a two-dimensional electrically insulated cylinder were examined: 1) no heat conduction and a constant electrical conductivity of the liquid and 2) infinite thermal conductivity i.e. conduction and convective heat transfer is infinitely fast. Using the hypothesis of an infinite thermal conductivity, theoretical and experimental results were comparable for low viscosity solutions. The hypothesis of a well-mixed bulk fluid for low viscosity solutions in a static ohmic heater was validated. At high temperature, the model overpredicted the liquid temperature. They suggested that a more complex model was needed for intermediate cases where the rate of heat transfer is neither zero nor infinity or for other geometries. Free convection was included in some models but no study was performed on forced convection.

Sastry (1992a) described a model to predict particle and liquid temperatures in a continuous flow ohmic heater for mixtures of low viscosity liquid containing a high proportion of solids. It was assumed that a plug flow exists through the heater and that the liquid was well mixed. Simulations were performed for various scenarios. The presence of a large population of low electrical conductivity particles resulted in slow heating of the entire mixture and particles heated faster than the liquid. There was a danger of underprocessing if isolated low-conductivity particles entered the system. Residence time effect was also important as fast-moving particles can thermally lag the fluid but to a lesser extent than expected for conventional process systems. Fluid-to-particle heat transfer coefficient was found to have a minor role on heating rates.

Orangi and Sastry (1998) presented a 3D model that predicts the temperature distribution in a solid-liquid mixture considering both axial and radial variations of the electric field and the fluid temperature in a continuous ohmic heater. The effect of various parameters on temperature distributions was studied. For typical values of electrical conductivity of liquid and solid phases, a thermal inversion point occurred, where the heating rate of the solid phase exceeded that of the liquid. When electrical conductivities were not widely apart, the effect of increased heat transfer coefficient was simply one of reducing interphase temperature difference. When phase electrical conductivities differed markedly, one phase heated significantly faster than the other did. The interphase energy flux was dictated more by temperature difference than heat transfer coefficient. Particle size had a small effect on overall heat transfer.

Only two papers have dealt with the operability of a continuous ohmic heating process for liquids only. Muller *et al.* (1994) reported on the behaviour of non-Newtonian liquids in a continuous ohmic heater. Temperature dependency on thermophysical properties was considered. Maximum temperatures were found close to the wall. Therefore, wall cooling was suggested as being necessary to ensure the uniformity of heating. Velocity profiles were mainly determined by the difference in viscosity between the wall and the centre of the heater. It was found that non-Newtonian behaviour became important only when the flow behaviour index was less than 0.6. The heater design was best characterised by Graetz number (Gz). Design with lower Gz (i.e. smaller heater radius and longer tube lengths or lower liquid throughput) was reported to exhibit a more uniform temperature distribution.

Quarini (1995) studied the thermohydraulic behaviour of a liquid flowing into a vertical continuous ohmic heating column, assuming it is a cylindrical pipe, at steady state. The radial and azimuthal flow velocities were zero and the centre of the pipe was a point of symmetry. The usual boundaries were applied at the wall i.e. zero velocity and prescribed temperature or heat flux. The bulk vertical or axial temperature gradient was a constant. Thermophysical properties were assumed to be independent of temperature except for density. Simplified momentum and energy differential equations were normalised and scaled to obtain dimensionless equations. At low volumetric heating rate and adiabatic walls, the flow distribution was parabolic for laminar flow and the temperature distribution was fairly flat as in usual forced convection. As the volumetric heating rate was increased, both the flow and temperature distributions began to change. The highest temperature occurred at the wall. The velocity profile was flat in the middle of the tube. The velocity rose to its peak before dropping to zero at the walls. It was found that if heating and flow rates were such that buoyancy became important, natural convection forces could dramatically change the flow and temperature distributions within a continuous ohmic heater. In ohmic heating, the aim should be to avoid temperature peaking of foods in regions of low flow. Suggested possible means of enhancing uniformity were cooling of the containment walls of the column and engineering desired conductive-temperature characteristics of foods.

In both Muller's and Quarini's models, there was no experimental validation performed. Muller's model is the most realistic one for non-Newtonian liquids ohmically treated in a collinear system. As reported in Chapter 7, the flow behaviour index of hydrocolloid solutions is likely to be less than 0.6. Therefore, the contribution of the viscosity is expected to be important.

The objective of this work was to describe the electric, flow and thermal behaviour of non-Newtonian fluids ohmically treated in a continuous heater and to validate the model experimentally.

DEVELOPMENT OF THE MODEL

Thermal behaviour

The thermal problem for the fluid is based on the energy balance. It requires the inclusion of the heat conduction, convection and heat generation yielding to the following equation:

$$\nabla\left(k_f \, \nabla T_f\right) \; + \; Q_f \; = \; \rho_f \, C_{pf} \, \frac{\partial T}{dt} \; + \; \rho_f \, C_{pf} \; v \cdot \nabla T \qquad [8.1]$$

In cylindrical coordinates, there are three directions i.e. r, θ and z. However, in this particular case, only the radial and axial directions are important. At steady state, there is no variation of temperature with time for a particular position. v is the convective velocity. Moreover, the fluid is assumed to possess a convective v only in the z direction, similar to that for a non-Newtonian fluid in a tube flow. For the special case of negligible radial convective velocity variations, the fluid heat transfer problem can be reduced to a one-dimensional computation. It is also assumed that there is no heat loss to the surroundings and that the tube is insulated:

$$\nabla\left(k_f \, \nabla T_f\right) \; + \; \dot{Q}_f \; = \; \rho_f \, C_{pf} \, v_z \cdot \frac{\partial T}{\partial z} \qquad [8.2]$$

The conduction in axial direction can be neglected because the term will be very small as compared to the axial convection resulting in the following equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r \, k_f \, \frac{\partial T}{\partial r}\right) + \dot{Q}_f \; = \; \rho_f \, C_{pf} \, v_z \, \frac{\partial T}{\partial z} \qquad [8.3]$$

The initial and boundary conditions are the followings: 1) inlet temperature constant and uniform, 2) axial symmetry, $\frac{\partial T}{\partial r}=0$ at r=0 3) insulated wall, $\frac{\partial T}{\partial r}=0$ at r=R. A particular case would be that the temperature gradient throughout the tube, i.e. in the z direction, is a constant (Quarini, 1995) which would occur at steady state.

Electric field distribution

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

$$\nabla(\sigma_f \cdot \nabla V) = 0 \qquad [8.4]$$

The electrical conductivity is temperature dependent. The value of σ increases with temperature as follows:

$$\sigma_f = \sigma_{25} + K_T\,(T-25) \qquad [8.5]$$

Therefore, the solution of the Laplace equation is dependent on the temperature distribution in the spacing tube. In cylindrical coordinates, the electric field distribution of the spacing tube between two electrodes can be calculated by:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\sigma_f\frac{\partial V}{\partial r}\right)+\frac{\partial}{\partial z}\left(\sigma_f\frac{\partial V}{\partial z}\right) = 0 \qquad [8.6]$$

The general volume based heat generation rate is given by:

$$\dot{Q}_f = \sigma_f\left(\nabla V\cdot\nabla V\right)=\left|\nabla V\right|^2\sigma_f \qquad [8.7]$$

In cylindrical coordinates, the volumetric heat generation term is:

$$Q_j = \sigma_f\left(\left(\frac{\partial V}{\partial r}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right) \qquad [8.8]$$

The boundary conditions are: 1) axial symmetry, 2) electrically insulated wall, 3) top and bottom electrodes with a fixed potential.

Flow behaviour

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

$$\rho\left(\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_z}{dz}\right) = -\frac{\partial p}{\partial z} + \rho g_z + \frac{1}{r}\frac{\partial}{\partial r}\left(\eta_a\, r\frac{\partial v_z}{dr}\right) + \frac{\partial}{\partial z}\left(\eta_a\frac{\partial v_z}{\partial z}\right) [8.9]$$

Again, the azimuthal, θ, direction component is assumed negligible. In this equation, a natural convection term arises from the temperature difference between the wall and the centre of the tube (ρg_z). Radial velocities (v_r) in the system are two orders of magnitude smaller than the axial velocities (Muller *et al.*, 1994); therefore viscous dissipation due to radial velocities can be neglected. Making the usual Boussinesq approximation in which the density is allowed to vary with temperature in the buoyancy term:

$$\rho = \rho_o\left[1+\beta\left(T-T_o\right)\right] \qquad [8.10]$$

Since, the flow velocity in the radial direction (v_r) is zero and the system is at steady state, this equation is greatly simplified:

$$\rho v_z \frac{\partial v_z}{\partial z} = -\frac{\partial p}{\partial z} + g \rho_o \beta (T - T_o) + \frac{1}{r}\frac{\partial}{\partial r}\left(\eta_a r \frac{\partial v_z}{\partial r}\right) \qquad [8.11]$$

The velocity in the z-direction is a function of the radial position and will be determined by the flow regime. RTD of particulate foods was investigated by Kim *et al.* (1996a) both visually and using Hall effect sensor magnet (Tucker and Withers, 1992) for a 35 % total solids content in a sauce. The flow characteristic was situated between a laminar flow limit and a plug flow. Although a plug flow situation is usually assumed for high proportion of solids, Kim *et al.* (1996a) suggested using a laminar flow residence time limit as a conservative and safe practice. The flow behaviour is also dependent on the viscosity of the fluid. Assuming a fully developed flow at the inlet, the velocity for a power law non-Newtonian fluid fully developed flow can be found from the following equation at any radial position:

$$v_z(0, r) = \frac{v}{\pi R^2}\left(\frac{3n+1}{n+1}\right)\left[1 - \left(\frac{r}{R}\right)^{\frac{n+1}{n}}\right] \qquad [8.12]$$

The viscous energy dissipation in a liquid is caused by the shear stress that one layer within the liquid exerts on the next. Models have been used to describe the flow behaviour of hydrocolloid solutions as a function of shear stress and shear rate, the most common being the power law:

$$\tau = m \dot{\gamma}^{n} \qquad [8.13]$$

The viscosity, which changes with the shear rate, is termed apparent viscosity η_a. The term apparent implies a Newtonian type of measurement to a non-Newtonian system:

$$\eta_a = \frac{\tau}{\dot{\gamma}} = m \dot{\gamma}^{n-1} \qquad [8.14]$$

Both the consistency coefficient (m) and the flow behaviour index (n) are temperature dependent. The effect of temperature on both the consistency coefficient (m) and the flow behaviour index (n) can be evaluated using the Turian approach (Turian, 1964) approach (Chapter 7):

$$\log m = \log m_o - A_1 T \qquad [8.15]$$

$$n = n_o + A_2 T \qquad [8.16]$$

The model developed for the typical heater, as described by equation 8.3, 8.6, 8.8 and 8.11, is solved with appropriate electrical conductivity (equation 8.5), viscosity (equation 8.14) that is temperature dependent (8.15 and 8.16). Viscosity, electrical conductivity, specific heat, thermal conductivity and density values are needed as input data for the model. Equation [8.12] is used to calculate the velocity profile at the inlet.

Finite element

The resulting partial differential equations (PDE) in real systems are highly non-linear because of the temperature dependence of physical and thermal properties. Because of its flexibility at handling complex geometries and a variety of boundary conditions, the Finite Element Method (FEM) was used to solve this system of equations. Computer simulations were performed on a PC (Pentium 2, 400 MHz, 256 MEG RAM and 13 GIGA HARD DRIVE) using a commercial Computational Fluid Dynamics software package (FIDAP, version 8.01, Fluent Inc., Lebanon, NH).

Figure 8.1 shows the dimensions of the typical collinear ohmic heater with two heating sections to be modelled along with initial and boundary conditions for the temperature and electric field and flow. An axi-symmetric problem was assumed using cylindrical coordinates. Quadrilateral elements with four nodes were used to generate the mesh, as was suggested by Uemura *et al.* (1996a). A total of 7864 elements were necessary for the model to converge while combining the energy and flow equations. Figure 8.2 represents the mesh generation for the ohmic heating column to be modelled.

An iterative procedure was used to establish time-temperature, velocity and electric field distribution profiles within the fluid during ohmic heating both in space and time. Starting from an estimate of the initial temperature throughout the ohmic heating column, properties (electrical conductivity, specific heat, thermal conductivity, viscosity

Axis or r = 0

$$\frac{\partial T}{\partial r}=0,\ \frac{\partial v_z}{\partial r}=0,\ \frac{\partial V}{\partial r}=0$$

$v_r = 0,\ v_\theta = 0$

Wall or r = R

$$\frac{\partial T}{\partial r}=0,\ \frac{\partial v_z}{\partial r}=0,\ \frac{\partial V}{\partial r}=0$$

$v_r = 0,\ v_\theta = 0$

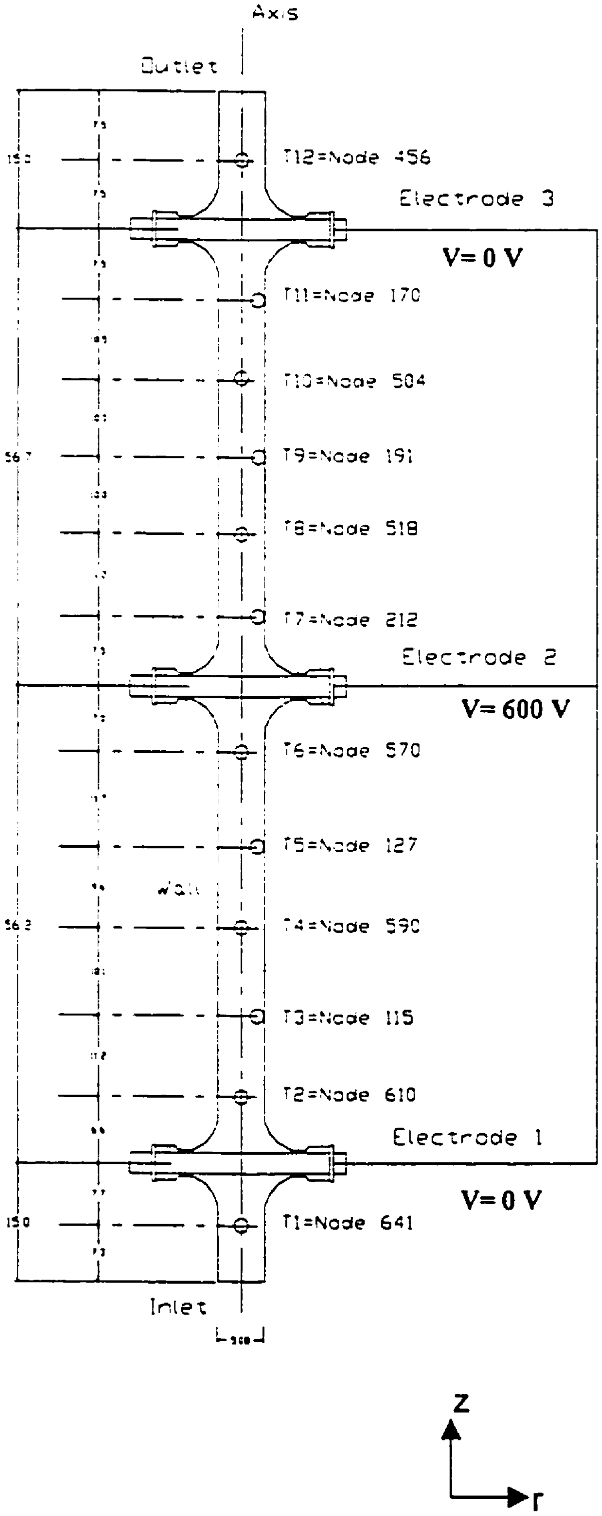
Uw = 10-50 W/m2 K

T air = 23°C

Inlet or z = 0

$V_z = v_z(0, r),\ T = T_{in}$

$v_r = 0,\ v_\theta = 0$



Dimensions are in cm

Figure 8.1 A collinear continuous ohmic heating column along with initial and boundary conditions

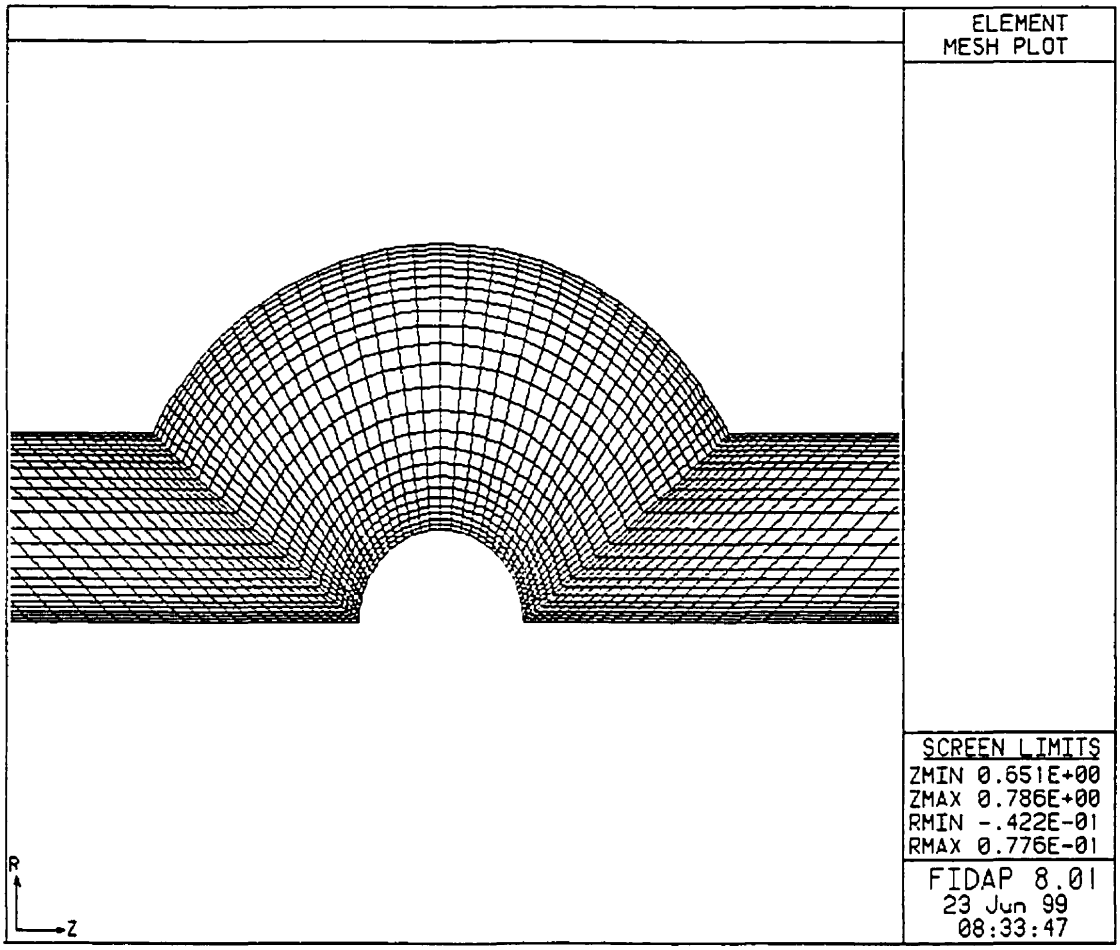


Figure 8.2 Mesh generation for the continuous ohmic heating column

and density) are calculated. The momentum and Laplace equations are solved to obtain the velocity and the electric field distribution at steady state. These are taken as initial conditions at t=0. For the next time increment, the momentum, Laplace and energy equations are solved and properties are calculated through an iterative adjustment until a convergence is reached for the solution at this specific time increment. Convergence is attained by adjusting the number of elements and the time step and certain parameters specific to the successive substitution solver, which was used. A loop was used for each time increment for this transient non-linear problem. A diagram of the algorithm used to solve the model of this continuous ohmic heating system is shown in Figure 8.3.

MATERIALS AND METHODS

Carrier fluid preparation

The carrier fluid was 4 % (w/w) starch solution (Thermo-flo starch, NFPA 0934 lot #LF5919, National Starch and Chemical Corp., Bridgewater, NJ, USA) with 1 % salt. Four hundred litres were hydrated and pregelatinized using a pilot scale commercial aseptic processing system (Contherm Division, Alfa Laval Inc., Newburyport, MA) by continuously heating to 140 °C through the heating part of a vertical scraped surface heat exchanger (SSHE), passing through the holding tube, cooling to 60 °C through the cooling part of SSHE. The fluid was fed using a variable speed positive displacement tri-lobe pump (Albin Pump, Atlanta, GA, USA).

Continuous ohmic heating unit

As presented in Figure 8.4a, the continuous ohmic heating unit is a collinear heater similar to the APV ohmic heater for particulate liquid foods. The electric field distribution is parallel to the flow of product. The continuous ohmic heating unit is assembled from two basic units: three electrode housings and two spacer tubes or heating sections. Electrodes are made from titanium. All internal surfaces in contact with the

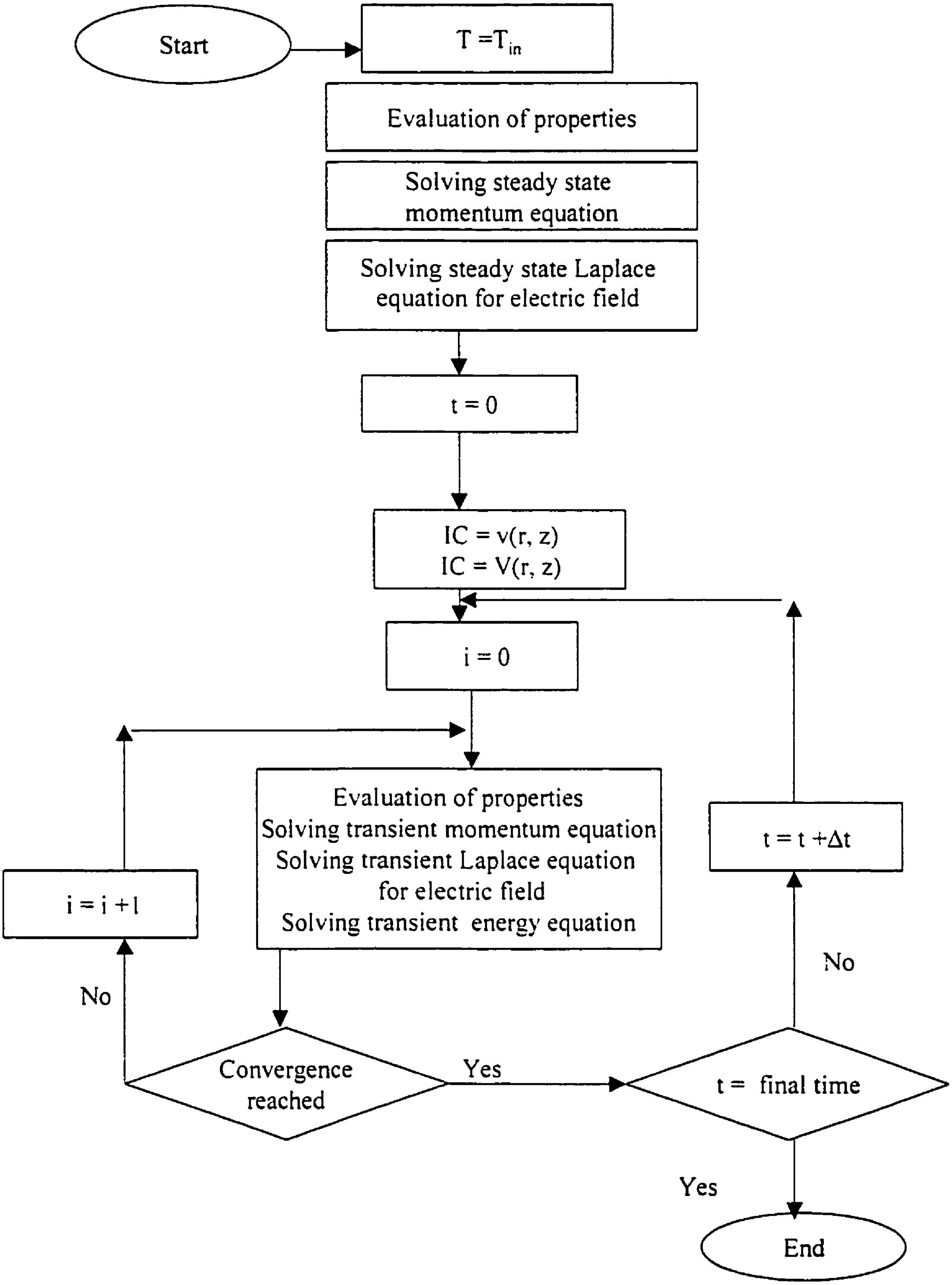
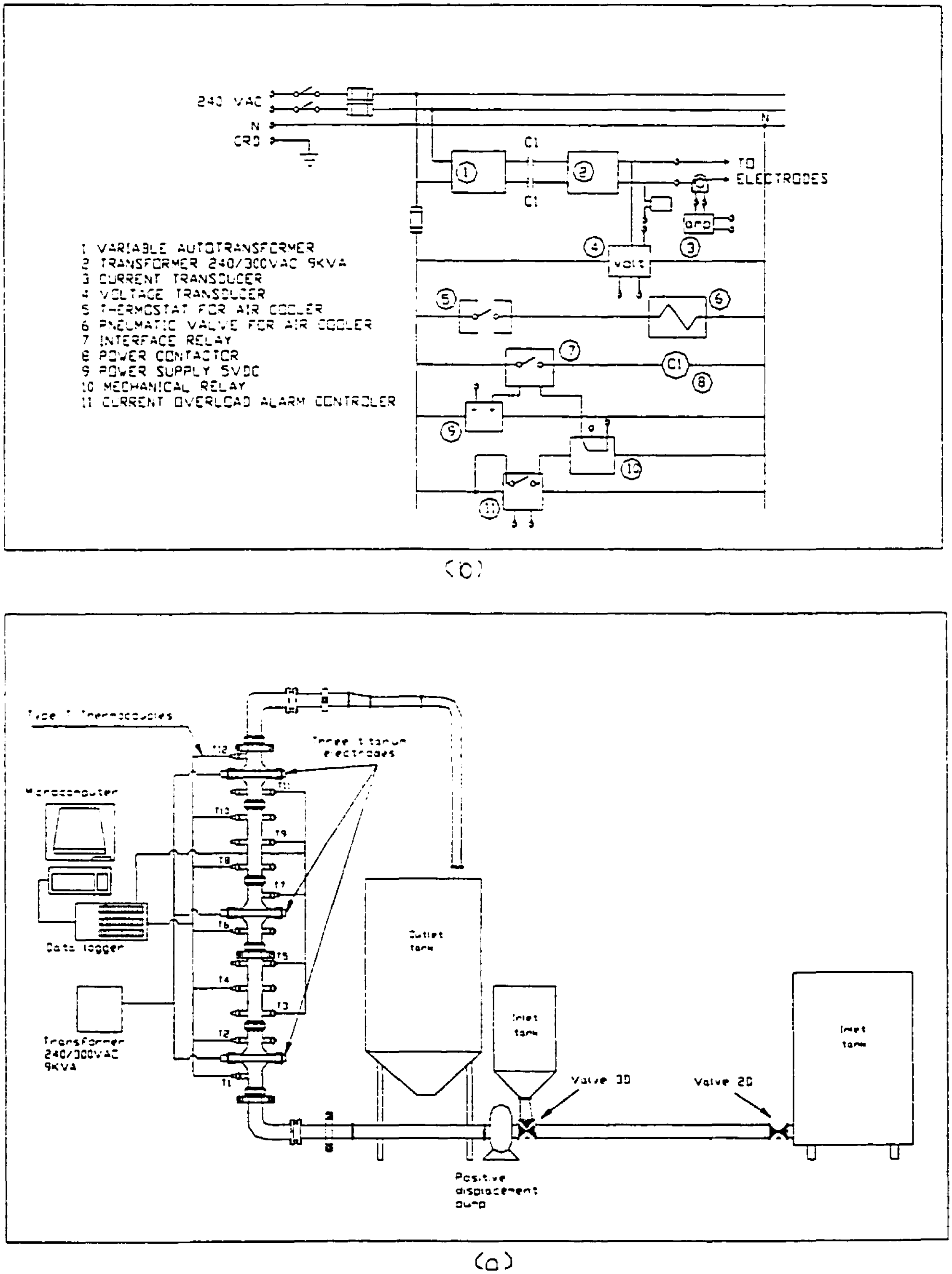


Figure 8.3 An algorithm to solve the theoretical model



(b)

(a)

Figure 8.4 (a) Schematic of the continuous ohmic heating unit
(b) Electrical power unit

food are constructed from insulating glass material except for the electrodes. The internal diameter of the glass tube is 5.08 cm. The length of the heating sections i.e. the space between the two first electrodes is 56.2 cm whereas for the other heating section, the length was 56.7 cm. A power unit (Hammond manufacturing, S87853, Guelph, ON, Canada and Bectrol Technologies Inc., St. Hyacinthe, QC, Canada) was used to generate the necessary electrical field at the three electrodes. It includes: a variable transformer, an isolation transformer, a voltage transducer, a current transducer, power relays and fuses. A maximum of 900 V for the voltage and 10 A for the current were the physical limits supplied by the power unit. A schematic of the electric circuit of the continuous ohmic heating unit is shown in Figure 8.4b.

A positive displacement pump (ALBIN Pump SLP-220, Atlanta, GA, USA) was used to flow the food product vertically from the bottom to the top between the electrodes from an inlet tank to an outlet plastic tank. First. the fluid was pumped horizontally on a 3-m length. Then, the fluid was passing through the two vertical ohmic heating sections (2 m). On the last part of the horizontal cylinder at the exit of the pipe, the length of the pipe was 55.8 cm. It was followed by a vertical pipe of 68.5 cm to feed the outlet plastic tank. Three levels of flow rate were selected : 1 l/min, 2.5 l/min and 10 l/min.

A constant voltage was applied to the three titanium electrodes. Six Teflon coated type T thermocouples (Omega Engineering, Stamford, CT, USA) were installed to measure the temperature of carried fluid at the centre of the cylinder (T1, T2, T4, T6, T8, T10 and T12). As well, six Teflon coated type T thermocouple were also used to determine the temperature of the fluid close to the wall (T3, T5, T7, T9 and T11) as shown in Figure 8.4a. Temperature, current and voltage were monitored and recorded at 10 s interval using a data logger (Model 2225, John Fluke MGF Co. Inc., Everett, WA, USA).

Moreover, each thermocouple position corresponded to a specific node of the mesh used for modelling purposes. Corresponding nodes with respect to thermocouple positions were already presented in Figure 8.1. These were used to compare time/temperature profiles from experiments to those predicted from the theoretical model.

Measurement of thermophysical and electrical properties

Density

The density of hydrocolloid solutions was measured using graduated pipets. First, each pipet was weighed. A solution sample was introduced in the empty pipet to a required precise volume. The pipet was weighed again. The weight of the solution was determined by difference between the weight of the full pipet and the empty pipet. The ratio of the weight of solution to the volume resulted in the density of the sample.

Specific heat

Sample specific heats were determined using a modulated differential scanning calorimeter (MDSC 2910, TA Instruments Inc., New Castle, DE, USA) with a nitrogen cooling system. Temperature modulation (sinusoidal oscillation) of MDSC separates total heat flow into its reversing (specific heat related) and non-reversing (kinetic) components. Therefore, specific heat values obtained by MDSC are direct and precise.

Into an aluminium pan, 10-15 mg of sample was placed and the pan was hermetically sealed. A sealed empty pan was used as a reference. The sample was scanned at a heating rate of 3 °C/min over a temperature range of 20-100 °C. An 80 s modulation period (single cycle) and ±1 °C amplitude were applied. Helium was used as a purging gas (25 ml/min). The operating conditions were selected according to the instructions manual which reported that the heating rate should be 5 °C/min or less and the modulation period should be 60 s or more under helium purging for the best accuracy of the specific heat.

Pure Milli-Q^{TM} (System ZDZO-115-94, Millipore Corporation, Bedford, MA, USA) water was used to calibrate. The calibration was done by comparing the measured specific heat of pure water with its literature value. Rahman (1995b) has given values for specific heat of foods.

Thermal conductivity

It is generally reported that a line heat source probe is the most suitable method to measure thermal conductivity for most foods (Murakami and Okos, 1989). Thermal conductivities were measured by the line heat source technique using the probe developed by Sweat *et al.* (1974). The probe (0.66 mm outside diameter) consisted of a constantan heater wire and a chromel-constantan E-type thermocouple. The constantan heating wire in the probe was connected to a power supply (6236B, Hewlett Packard Canada Ltd, Mississauga, ON, Canada). The probe heater was activated with a constant current of 0.201 A. When the current flows through the probe, heat can be generated gradually, resulting in a temperature distribution within the cylindrical sample. Time and probe temperature data were recorded every 0.1 s using a data acquisition system (Model Hydra 2520, John Fluke MGF Co. Inc., Everett, WA, USA) connected to a PC through an RS-232. The rate of temperature rise in the probe was directly related to the sample's conductivity. A linear regression line was fitted to the linear portion of ln (time) vs. temperature data by the least square method. Thermal conductivity of the sample was calculated using the following equation:

$$k = \frac{Q}{4\pi M} \qquad [8.17]$$

where M is the slope of the ln (time) vs. temperature curve. Q is the heat supplied by the probe (W/m) calculated from the resistance of the probe (R) and the current (I):

$$Q = RI^2 \qquad [8.18]$$

The overall resistance of the probe was determined by testing the resistance of pure glycerol solution at 21 °C with its known thermal conductivity. Samples were installed in a cylindrical copper container of 4 cm inside diameter and 6 cm of height. Samples were allowed to equilibrate at the temperature of measurement. The thermal conductivity of samples was measured at 20, 40, 60 and 80 °C. During the test, the copper container was capped with a plastic cover to avoid water loss. Values were found to increase linearly with temperature from 0.4 to 0.8 W/m²K which corresponded to values reported in literature (Rahman, 1995a). A regression was fitted to obtain the equation of thermal conductivities versus temperature.

Electrical conductivity

Electrical conductivities were measured for starch 4 % in the presence of 1 % salt as described in chapter 5. Electrical conductivities were plotted against the temperature. A linear regression was obtained and used as input data for the model.

Viscosity

Viscosities were measured as described in chapter 7 for starch at 4 % in the presence of 1 % salt at 4 temperatures (20, 40, 60 and 80 °C). The power law model was used to generate m, the consistency coefficient, and n, the flow behaviour index, at each temperature. A Turian approach was used to calculate the dependency of m and n with temperature. A linear regression (Equation 8.15 and 8.16) was obtained for each rheological parameter for upward and downward curves.

Table 8.1 lists thermophysical properties of starch 4 % and 1 % salt that were used in the model as input values.

RESULTS AND DISCUSSION

Steady state of the electric field distribution

Figure 8.5 represents the electric field distribution at steady state for 600 V solved using the Laplace equation. With three electrodes, the highest voltage was located at the middle electrode while the voltage was zero at both extremities. Since the polarity was inversed there was a distribution of the voltage in one direction for the first section and the opposite was found for the second section.

Table 8.1 Thermophysical property values for starch (4 %) and 1 % salt

Property	**Values**
Electrical conductivity, σ, at 25°C (S/m)	2.1098
Temperature coefficient, K_T, for σ (S/°C m)	0.04267
Upward curve	
Consistency coefficient, log m_o, (Pa.s)	0.45735
Temperature coefficient for m (1/°C)	-0.00801
Flow behaviour index, n_o	0.4892
Temperature coefficient for n (1/°C)	0.00117
Downward curve	
Consistency coefficient, log m_o, (Pa.s)	0.33683
Temperature coefficient for m (1/°C)	0.00664
Flow behaviour index, n_o	0.5656
Temperature coefficient for n (1/°C)	0.00105
Specific heat, Cp (J/kg °C)	4.078
Thermal conductivity, k, (W/m K)	0.34
Temperature coefficient for k (W/m K^2)	0.06
Density, ρ, (kg/m^3)	1002

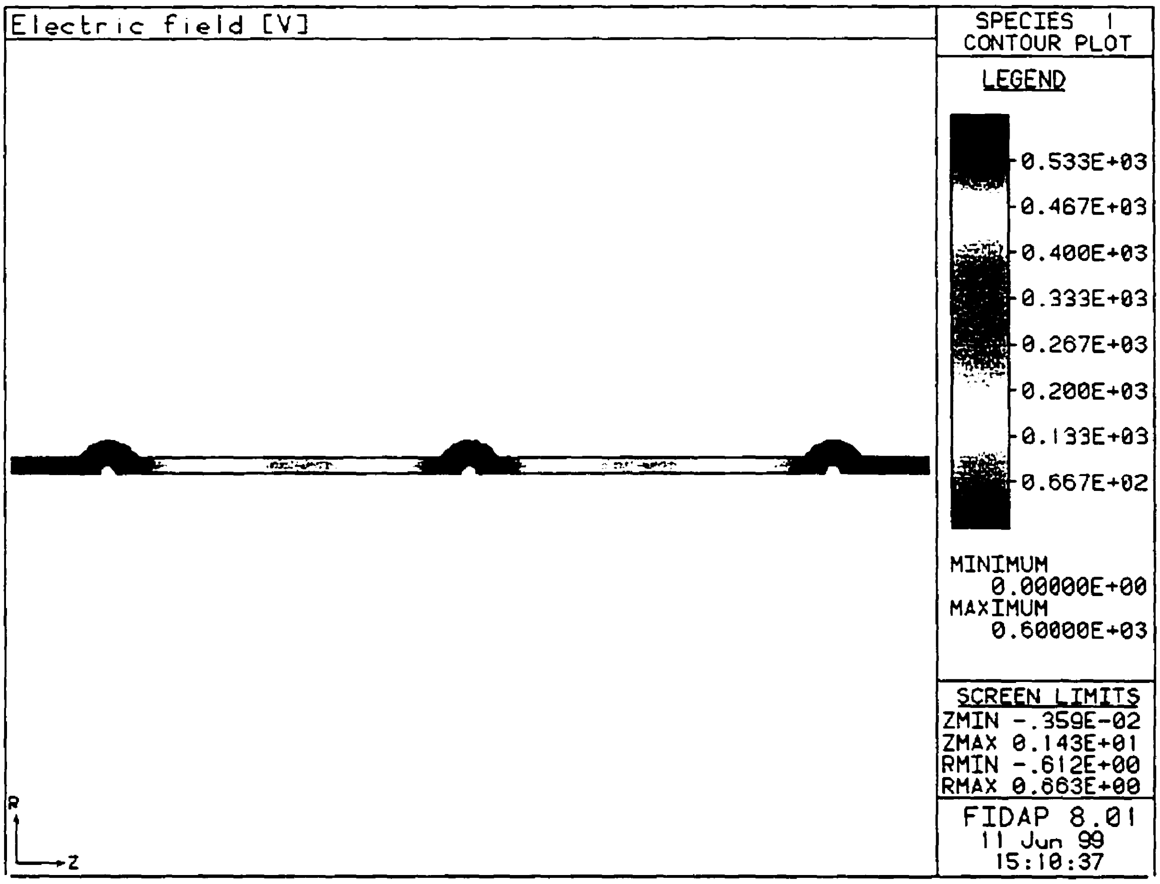


Figure 8.5 Steady state electric field distribution at 600 V

Energy balance during static ohmic heating

At first, only the energy equation was modelled. To validate the model, the ohmic heating column was filled with starch solution (4 %) and 1 % salt that remained still during the experiment. Two conditions of constant voltage were applied either 250 V or 500 V. These experiments were performed in duplicate. Figure 8.6 represents experimental data for static experiments in the continuous ohmic heating unit for these conditions. The highest temperature was always found at the centre of the tube and was quite uniform throughout the ohmic heating column. The temperature of thermocouples placed near the border of the tube was always lower than that at the centre, indicating that there was some heat losses to the surroundings. An evaluation of the heat transfer coefficient at wall (U_w) quantifying heat losses to the surroundings was performed based on these experimental data. This was used in further modelling for the continuous ohmic heating experiments.

A comparison between experimental and theoretical time/temperature profiles is shown in Figure 8.7. Both profiles were in good agreement. Therefore, using temperature dependent thermophysical and electrical properties, generated separately, as input data was found to be acceptable. As well, this mesh distribution was appropriate leading to convergence. Finally, it can be concluded that there was no significant free convection during experiments in this system as there was no discrepancy between experimental and theoretical time/temperature profiles, which assumed no free convection in its description.

Velocity profile without energy balance

For the three levels of flow rate (1 l/min, 2.5 l/min and 10 l/min), selected to generate experimental data, Reynold numbers were calculated. Flows were found to be laminar for all conditions. Other experiments performed on the use of an ultrasonic method to assess residence time distribution (RTD) characteristics of viscous liquids at 20 °C and 80 °C confirmed the calculations (results not shown). Therefore, the Navier-Stokes equation was solved to obtain a laminar velocity profile assuming a constant

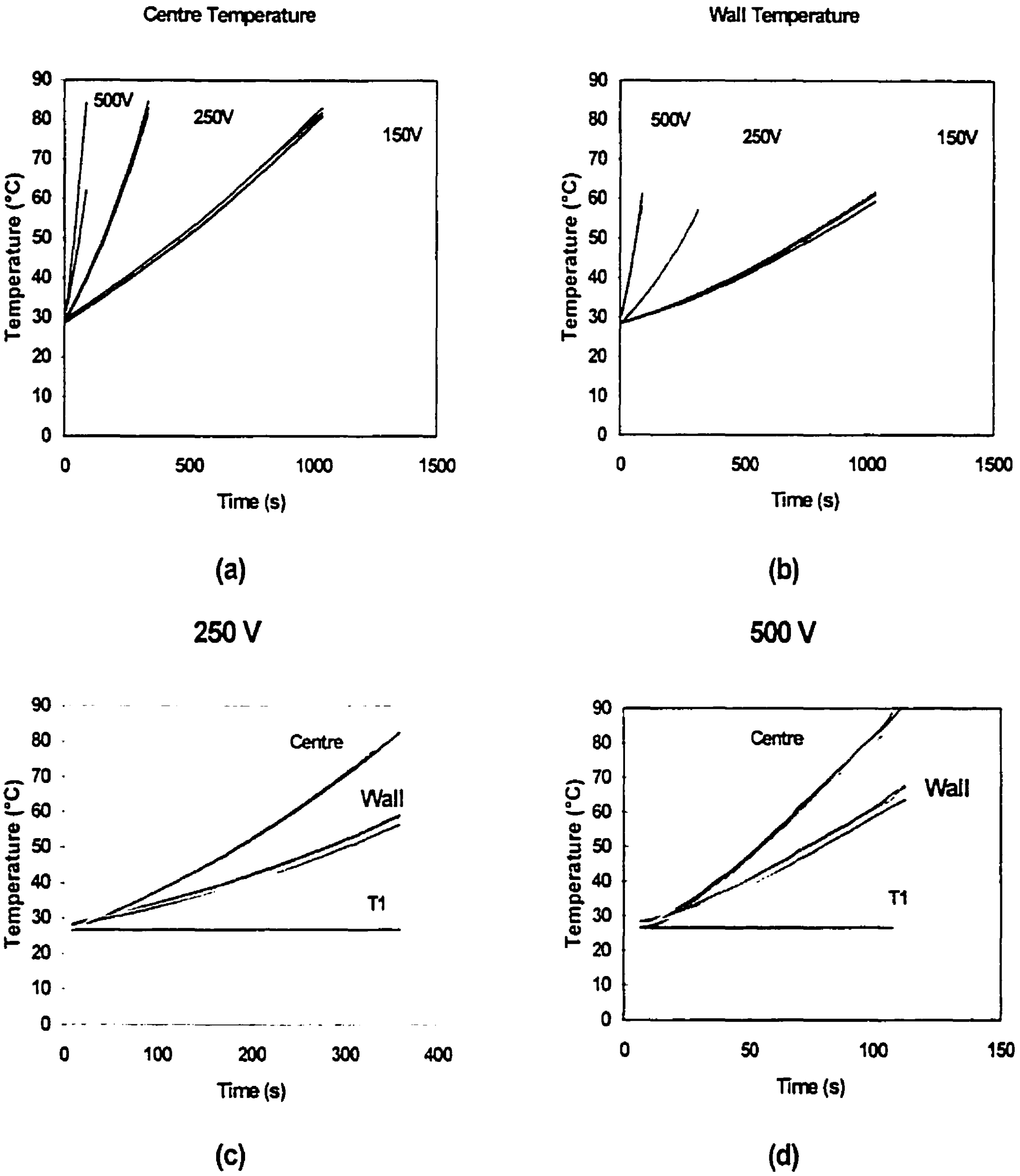
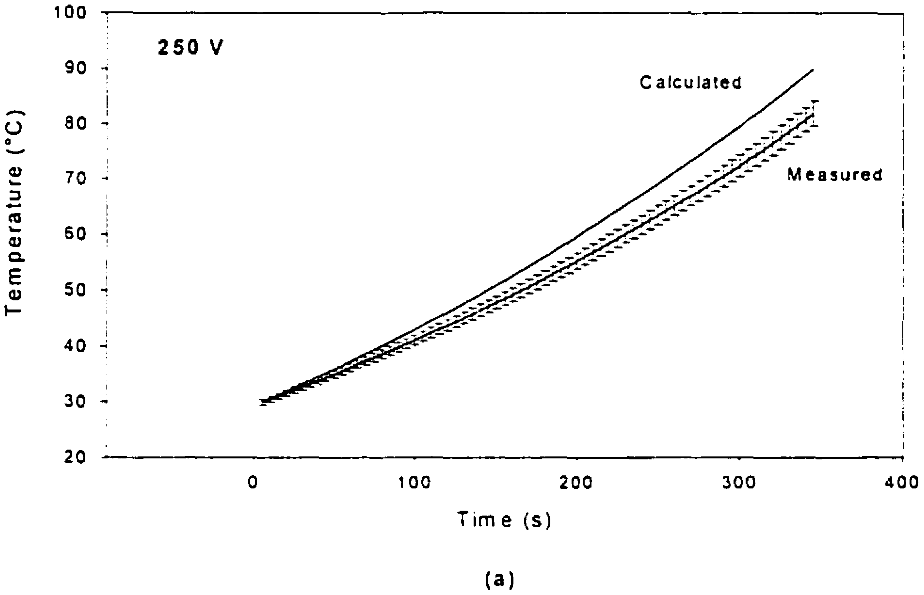
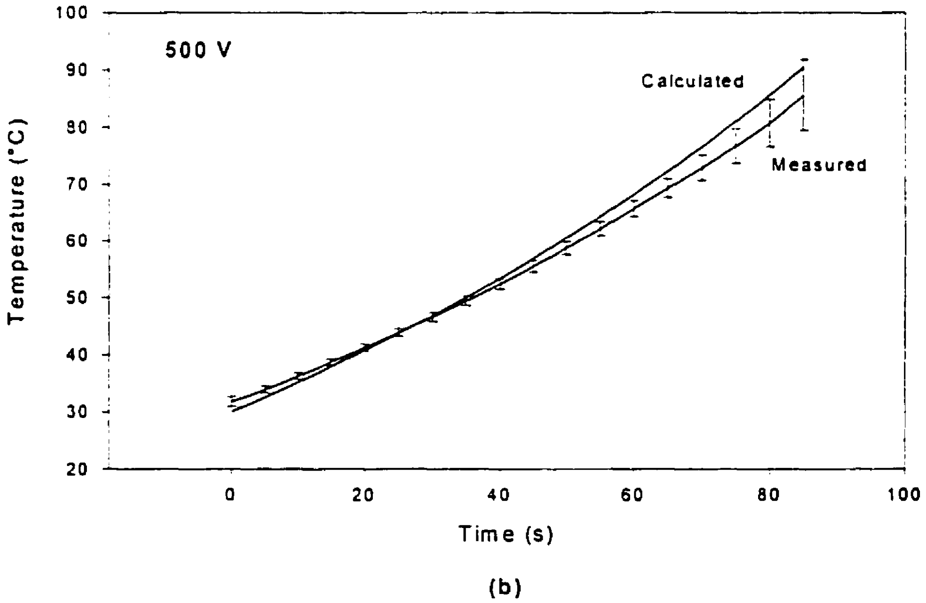


Figure 8.6 **Static experimental time/temperature profiles at the centre and the wall of the continuous ohmic heating unit at 150 V, 250 V and 500 V**



(a)



(b)

Figure 8.7 **Comparison of static experimental and predicted time/temperature profiles at the centre of the continuous ohmic heating unit at 250 V and 500 V**

viscosity at 0.2 Pa.s and a specific flow rate of 2.5 l/min. The z-component velocity along the continuous ohmic heating column is shown in Figure 8.8. The average velocity (v_{mean}) was calculated from the flow rate (2.5 l/min or 41.7 cm^3/s) and the cross-sectional surface area of the tube (20.26 cm^2), as being 2.06 cm/s ou 0.0206 m/s. The computed z-component velocities were found to vary from 0 at the wall to 0.043 m/s at the centre, which was the maximum velocity (v_{max}). Therefore, the momentum equation was validated as v_{max}/v_{mean} was equal to 2, the usual case for laminar flow. It is important to notice that the z-component velocity surrounding electrodes was considerably reduced due to the fact that the cross-sectional surface area of the tube was enlarged at these locations. It is generally well known that for a pseudoplastic fluid, $n < 1$, $v_{max} < 2\ v_{mean}$. However, it was not possible to validate that without coupling the three equations (momentum, Laplace and energy), which was performed in the next section of this chapter.

Coupled energy, momentum and Laplace equation

Experimental time/temperature profiles are shown in Figure 8.9 for several combinations of voltage and flow rate. For each experiment, a rapid increase of the temperature for each thermocouple was observed until steady state. A gradient of temperature in the z-direction was established and remained constant. The combination of voltage and flow rate will determine the time for the system to reach steady state and the typical temperature gradient throughout the continuous ohmic heating column giving a specific temperature rise of the fluid. As the voltage increased from 300 V to 500 V at 1 l/min, the time to reach the steady state was reduced approximately by half and the fluid temperature rise is greater throughout the ohmic heating column, 20 °C and 60 °C respectively. At a voltage of 250 V and a flow rate of 2.5 l/min, the temperature rise of the fluid was very small (8 °C). However at 600 V, a sharp temperature gradient was established throughout the ohmic heating column after 100 s for a temperature rise of 40°C. At 10 l/min and 600 V, a very small temperature gradient was obtained (results not shown). Using a flow rate of 10 l/min would require a much higher voltage to generate a significant rise in the fluid temperature throughout the continuous ohmic heating column.

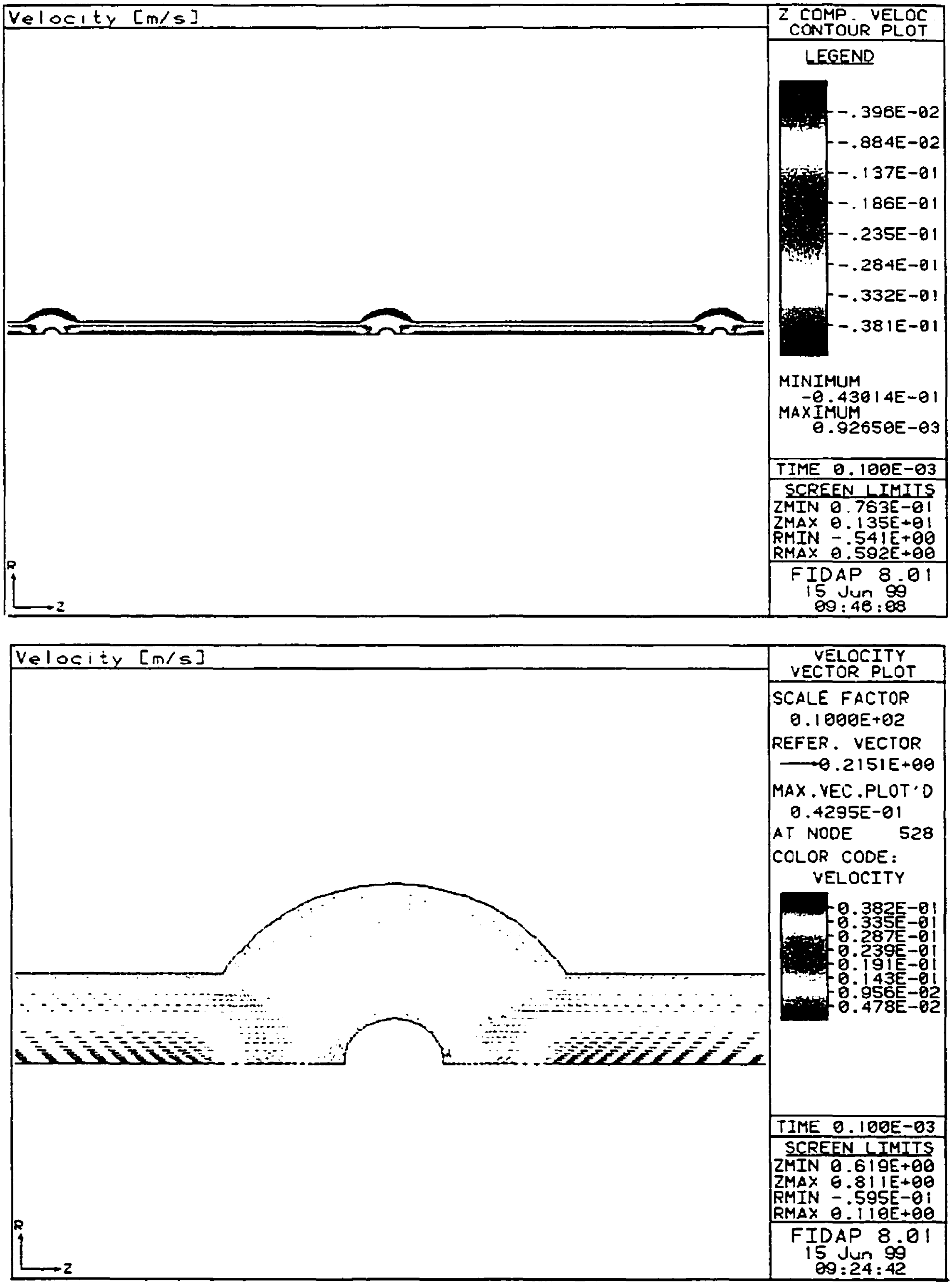


Figure 8.8 The z-component velocity along the continuous ohmic heating column without any temperature change

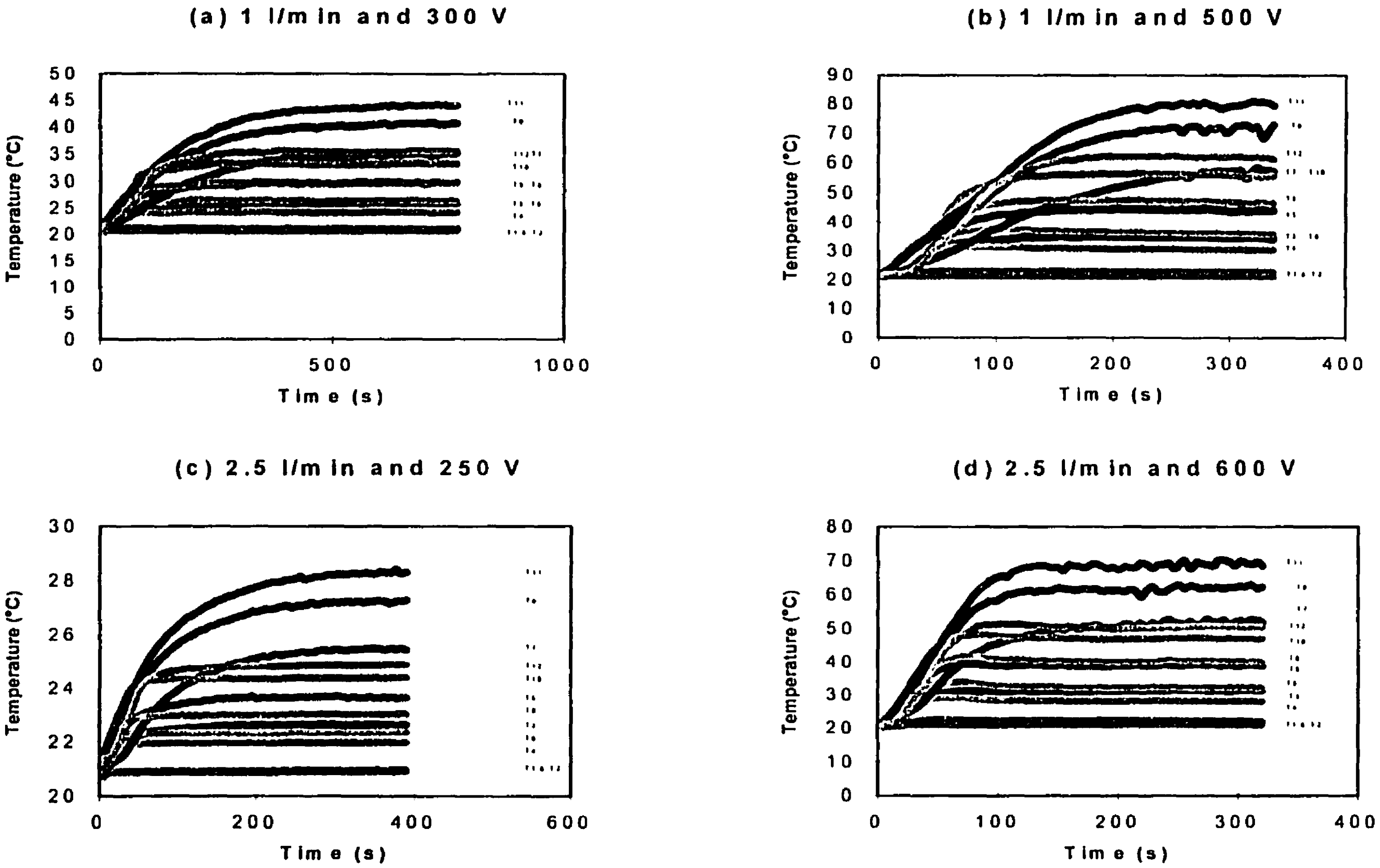


Figure 8.9 Experimental time/temperature profiles at the centre and the wall of the continuous ohmic heating unit (a) 1 l/min and 300 V (b) 1 l/min and 500 V (c) 2.5 l/min and 250 V (d) 2.5 l/min and 600 V

Since the power unit is limited to 900 V, this flow rate is obviously too high considering the physical limit of the system. The data indicated the necessity of voltage and flow rate optimisation in order to operate efficiently a continuous ohmic heating column for a specific product within the physical limits of the system and to obtain the desired temperature rise. Using this particular pilot scale continuous ohmic heating column, a flow rate of 2.5 l/min would probably be the optimal for a 4 % starch solution in the presence of 1 % salt. It should be noted that the flow rate of 2.5 l/min and 600 V was used to validate the theoretical model with experimental data.

Figure 8.10abc illustrates the simulated temperature profiles at different point in the continuous ohmic heating column. Each point is referring to an experimental thermocouple location. Simulated profiles have been considered for the following conditions: a) constant viscosity (0.2 Pa.s) while electrical conductivity and thermal conductivity are dependent upon the temperature, b) varied viscosity while the electrical (0.5 S/m) and thermal conductivity are constant and c) viscosity, electrical and thermal conductivity are temperature dependent with a heat transfer coefficient at the wall (U_w)of 50 W/m^{2}K.

As shown, there was an increase of the temperature for each point as a function of time followed by a steady state which was observed for all selected conditions. It should be noted that the same trend was found for the experimental results. This indicated that the model was able to predict the transient and the steady state heat transfer.

A gradient of temperature was observed throughout the ohmic heating column along the z direction since temperature profiles were different from one point to another. The temperature of the hydrocolloid solution at each thermocouple location increased along with the movement from the inlet towards the outlet of the column. This is due to the residence time that the fluid spent between the two electrodes. Experimental data showed the same trend for the temperature gradient. There was also a difference between the temperature at the wall and at the centre of the column. Contrary to static ohmic heating experiments, temperatures were always higher at the wall than at the centre of the column. These observations are due to the fact that the centre points have the higher velocity than the points close to the wall so the residence time of the fluid at the wall is longer that the residence time of the fluid at the centre of the column.

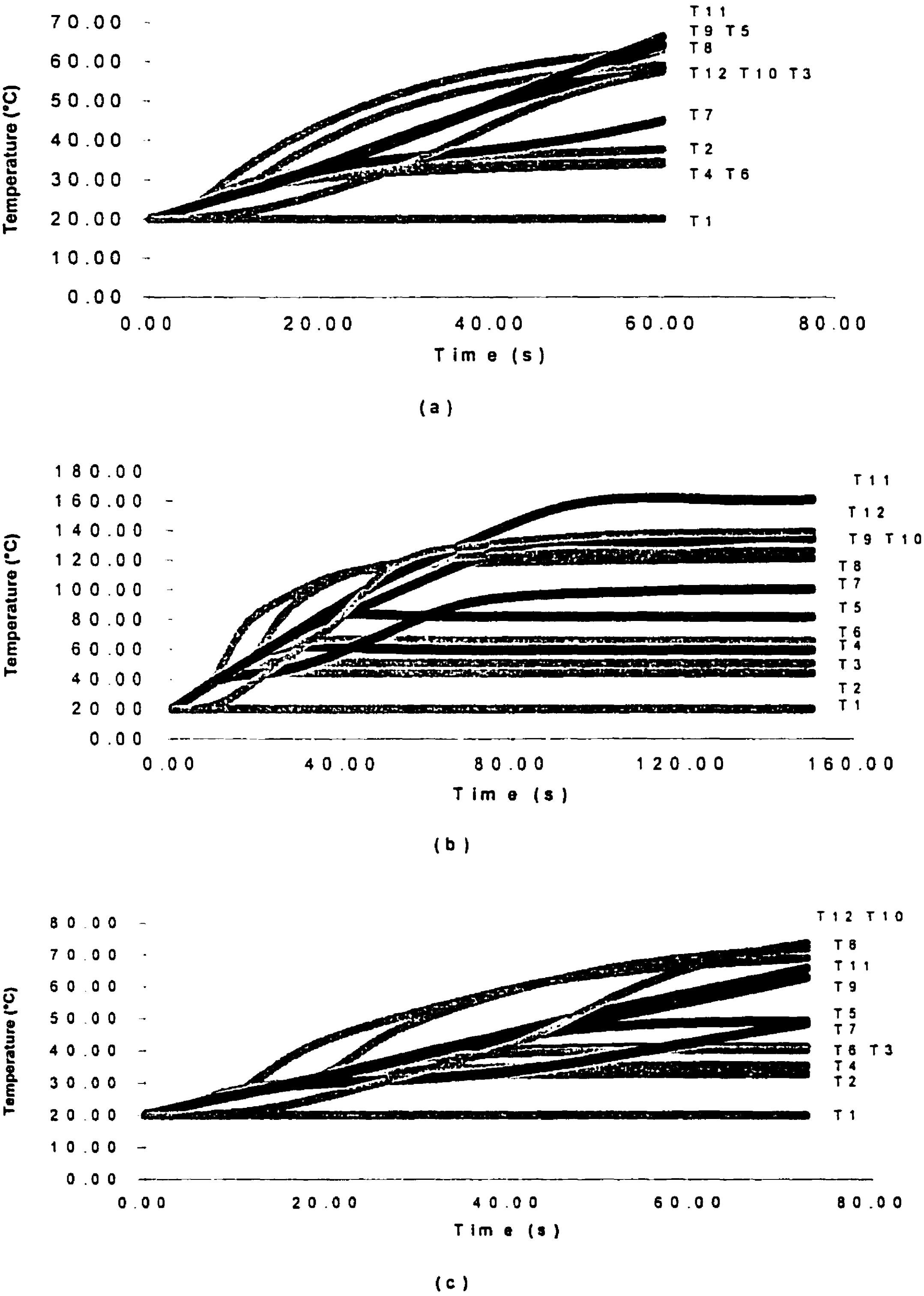


Figure 8.10 Comparison of experimental and predicted time/temperature profiles obtained in the continuous ohmic heating unit at 600 V and 2.5 l/min (a) constant viscosity at 0.2 Pa.s (b) power law model and constant electrical conductivity (c) power law model and variable electrical conductivity and $U_w = 50 W/m^2K$

Figure 8.10b revealed that using an average electrical conductivity at 0.5 S/m would not generate the appropriate temperature profile at steady state in comparison to a steady state profile. It was definitely necessary to introduce a temperature dependent electrical conductivity.

Since the calculated steady state temperature profiles were higher than the obtained experimental data in Figure 8.10b, an overall heat transfer coefficient of 50 W/m^2K was introduced in Figure 8.10c along with temperature dependent electrical, thermal and rheological properties to decrease these steady state temperatures. This caused a reduction in temperature from 110 °C to around 70 °C at the point close to the outlet. Heat losses to the surroundings were assumed to occur due to free convection from the continuous unit to the air. Values of free convection heat transfer coefficients to the surrounding air are known to vary from 10-50 W/m^2 K.For static heater, Sastry and Palaniappan (1992c) have used an overall heat transfer coefficient of 56 W/m^2K. Moreover, Sastry (1992a) has already used a an overall heat transfer coefficient for a continuous flow of 20 W/m^2 K. Theoretical and experimental temperature profiles were found in good agreement.

CONCLUSIONS

A theoretical model describing the electrical, thermal and flow behaviour of hydrocolloid solutions in a continuous ohmic heating column was developed. At first, it was validated experimentally for the transient heat transfer when the continuous ohmic heating column was filled with starch (4 %) in the presence of 1 % salt. Solving simultaneously the equations of Laplace, Fourier and Navier-Stoke including temperature dependent electrical conductivities, viscosities and thermal conductivities, the transient heat transfer or the temperature profile at each thermocouple location and the steady state temperature gradient within the column was in good agreement with experimental data generated for starch (4%) with 1 % salt at a flowrate of 2.5 l/min and an applied voltage of 600 V. The model can be used to study the effect of several factors on the performance of a continuous ohmic heating column.

CHAPTER 9

GENERAL CONCLUSIONS AND RECOMMENDATIONS

In this thesis, the technical feasibility of ohmic heating for various hydrocolloids in solutions was investigated thoroughly. In order to study the ohmic heating technology, several static cells were designed and built. As well, a continuous ohmic heating unit was constructed and installed. A review of literature pertaining to ohmic heating of hydrocolloids solutions indicated that there was little information available on these fluids used as such or, as carrier liquids for particulate foods during ohmic processing. The major role of hydrocolloids in food preparations is based on water-binding capacity and their ability to modify the rheological behaviour in order to obtain a desired functionality suited to the application. The selection of hydrocolloids in food formulations is dependent on conditions of utilisation. Therefore, careful precautions should be taken in the selection of hydrocolloids in sauces if one wants to apply ohmic heating.

The study consisted of five main steps: 1) the measurement of electrical conductivities and ohmic heating behaviour of selected hydrocolloid solutions in a static cell; 2) the determination of salt and acid effect on electrical conductivities, time/temperature profiles and heating rates of formulated hydrocolloid solutions in a static cell; 3) the identification of important physical factors affecting electrical conductivity measurement and heating rate in a variety of specifically designed static cells; 4) the measurement of rheological properties of these selected hydrocolloid in water solutions and finally, 5) the modelling of ohmic heating of selected hydrocolloids in a continuous pilot scale integrating input data generated in previous four steps.

First, ohmic heating behaviour and electrical conductivities associated with hydrocolloid type and concentration in water solutions were found to exhibit marked differences. For all hydrocolloids, as the concentration of hydrocolloid in solutions increased, electrical conductivities and heating rates increased. Carrageenan solutions gave the highest electrical conductivities and the shortest time to raise their temperature. It was followed by xanthan solutions. Pectin and gelatin samples were found to have same electrical conductivities and heating rates. Starch solutions were the least effective during ohmic heating. Major differences in electrical conductivity values were observed to be attributed to the ash content of hydrocolloid powders. Heating was found to be uniform throughout samples for carrageenan, pectin (1-3 %) and gelatin. However, some non-uniformities in temperature profiles arose in xanthan and starch solutions mainly attributed to their rheological properties and the temperature dependency of these properties.

Electrical conductivities and heating behaviour associated with hydrocolloid type (carrageenan, xanthan, pectin and starch) and concentration in water solutions were found to be influenced by the salt content and to a much lesser extent to their pH that was varied by the addition of citric acid. At low salt concentration (0.25 to 0.75 %), carrageenan and xanthan gave the shortest heating time and the highest electrical conductivities. That was followed by pectin and finally starch. At the highest salt concentration (1%), the effect of salt overcame the effect of hydrocolloid type giving similar electrical conductivities and time/temperature profiles for all hydrocolloid solutions.

Specific cells were designed to study the configuration factors (distance between and cross-sectional surface area) of cells as well as voltage gradient on electrical conductivities and heating rates. Voltage gradients had a major impact on time/temperature profiles but no effect on electrical conductivities. For all hydrocolloid solutions, a minimum voltage gradient of 15 V/cm was necessary to obtain the same heating rate as in conventional in-container sterilisation except for xanthan solutions which showed a better performance upon ohmic heating even at the lowest voltage gradient (5.26 V/cm). Increasing the cross-sectional surface area of electrodes had a negligible impact on time/temperature profiles, while increasing the distance between electrodes had a major effect. The physical limitation to the application of ohmic heating in these cells was the current, as 10-12 A was quickly attained in some conditions. A simplified theoretical model was developed considering the physical geometry of cells, only the heat conduction with no heat losses to the surroundings. Experimental time/temperature profiles were found to be in good agreement with results of computer simulations. This model could be used to simulate other conditions without performing experiments and even to establish design criteria for static cells.

Considering the lack of information on ohmic heating of viscous liquids, all information obtained in static cells proved to be very useful in evaluating the effect of type of hydrocolloids and their concentration in water solutions as well as formulation effects such as salt and citric acid addition. Electrical conductivity data generated at these low voltage alternating current conditions could also be used to design radio-frequency or pulse electric field treatments. Furthermore, experiments with specifically designed cells helped us to understand the relationship between configuration factors and electrical conductivities and heating rates.

As rheological characteristics were found to influence the uniformity of ohmic heating behaviour in static cells, experiments were performed to characterise these selected food hydrocolloids in water solutions as affected by temperature, concentration (carrageenan 1.5, 1.7 and 1.9 %; pectin 2.3, 2.5 and 2.7 %; starch 3.8, 4 and 4.2 % and xanthan 1.6, 1.8 and 2 %) and shear rate (100 s^{-1}, 200 s^{-1} and 300 s^{-1}) in the presence of 1 % salt. Only one concentration of each hydrocolloid in water solutions was selected (carrageenan, 1.5 %; pectin, 2.5 %; starch, 4 % and xanthan, 2 %) to obtain an apparent viscosity of 0.2 Pa.s at 300 s^{-1} and 20 °C for the study of the effect of temperature on rheological properties. Concentration, temperature and shear rate effects on rheological properties were different depending on the type of hydrocolloids. For example, the concentration effect was quite dominant for carrageenan solutions. Xanthan was less affected by concentration but mostly by the shear rate. It was found that the power law model fitted very well shear stress/shear rate rheograms for starch and pectin. However, significant yield stresses were observed for carrageenan and xanthan. For these hydrocolloids, a Herschel-Bulkley model was more appropriate. Both the consistency coefficient (m) and the flow behaviour index (n) were sensitive to changes in temperature and concentration. A shear thinning behaviour was observed for all selected hydrocolloids for the upward and downward curves. As the temperature of the solution increased, m decreased and n increased. As the concentration of the solution was increased, m increased and n decreased. Carrageenan solutions showed the highest level of activation energy indicating a lower resistance of decreasing the apparent viscosity at elevated temperatures. Pectin resulted in a lower temperature sensitivity of the apparent viscosity than carrageenan and higher than xanthan.

A theoretical model describing the flow and the thermal behaviour of hydrocolloid solutions in a continuous ohmic heating unit was developed and solved using a commercial Computational Fluid Dynamics software package FIDAP. All the information generated experimentally in static cells for electrical conductivities as well as rheological properties were used as input data to test the model. Experiments were performed in the continuous ohmic heating unit using starch 4 % with 1 % salt. Time/temperature profiles were recorded at time intervals and along the geometry of the ohmic heating column until it reached steady state. At first, the voltage gradient distribution was established in the two sections at steady state. Secondly, the thermal model was validated for time/temperature profiles in static experiments conducted in the continuous ohmic heating unit. In addition, the model was validated for the flow behaviour without any field gradient applied and no elevation of temperature. Finally, all equations were coupled and time/temperature profiles at different locations were obtained and compared to experimental data and found in good agreement.

The technical feasibility of ohmic heating was assessed successfully for selected hydrocolloid solutions. The study has revealed a general need for data on electrical conductivities of these products. Rheological properties determined for various hydrocolloids will serve not only as a useful tool in mathematical modelling but also as a helping knowledge for the choice of hydrocolloids in food formulations. From the comparison between static ohmic heating and a conventional heating treatment, the limiting voltage gradient was determined for the best efficiency of ohmic heating with respect to the conventional treatment. It was the first time that a model of thermal, electric and momentum transfer for viscous liquids during continuous ohmic heating was validated experimentally. Validation of the model, developed for continuous systems, should be done under other conditions. Work is needed to better characterise the flow behaviour of liquids during ohmic heating. Finally, further studies are also needed to investigate the sensitivity analysis of important parameters in continuous ohmic processing that would have to be performed through modelling.

BIBLIOGRAPHY

Abdelrahim, K.A. 1994. Residence time distributions (RTD) of food particles and rheological properties of fluids under aseptic processing conditions. Ph.D. thesis. McGill University, Montréal, Canada.

Abdelrahim, K.A., Ramaswamy, H.S. 1995. High temperature/pressure rheology of carboxymethyl cellulose (CMC). Food Res. Intl 28(3): 285-290.

Abdelrahim, K.A., Ramaswamy, H.S., Marcotte, M., Toupin, C. 1993. Residence time distribution of carrot cubes in starch solutions in a pilot scale aseptic processing system. Food Res. Intl. 26 :431-441.

Abdelrahim, K.A., Ramaswamy, H.S., Doyon, G., Toupin, C.J. 1994. Rheology of carboxymethyl cellulose as influenced by concentration and temperature. Intl. J. Food Sci. Technol. 29: 243-253.

Abdelrahim, K.A., Ramaswamy, H.S., Grabowski, S., Marcotte, M. 1995a. Dimensionless Correlations for the Fastest Particle Flow in a Pilot Scale Aseptic Processing System. Lebensm.-Wiss. u-Technol. 28:43-49.

Abdelrahim, K.A., Ramaswamy, H.S., van de Voort, F.R. 1995b. Rheological properties of starch solutions under aseptic processing temperatures. Food Res. Intl. 28(5): 473-480.

Abdelrahim, K.A., Ramaswamy, H.S., Marcotte, M. 1997. Residence time distributions of meat and carrot cubes in the holding tube of an aseptic processing system. Lebensm.-Wiss. u.-Technol. 30 : 9-22.

Allen, K., Eidman, V. and Kinsey, J. 1996. An Economic-Engineering Study of Ohmic Food Processing. Food Technol. 50(5):269-273.

Anderson, A.K., Finkelstein, R. 1919. A study of the electropure process of treating milk. J. Dairy Science 2:374-406.

Anon. 1994. Le chauffage ohmique : à explorer. Cahiers des industries alimentaires 33:13-15.

Anon. 1996. Un pilote de traitement thermique en continu par chauffage ohmique. Cahiers des industries alimentaires 36:12-15.

AOAC. 1984. Method 31.012. 14e edition. Arlington VA.

Athayde, A.L., Ivory, C.F. 1985. The effect of AC fields on carrier-mediated transport. J. Membrane Sci. 23 : 241-256.

Aussudre, C. 1996. La concentration des fluides par chauffage ohmique. Presented at the Expose Chem' Elec. *Personal Communication.*

Awuah, G.B., Ramaswamy, H.S., Simpson, B.K. 1993. Thermal inactivation kinetics of trypsin at aseptic processing temperatures. J. Food Proc. Eng. 16:315-328.

Awuah, G.B., Ramaswamy, H.S. 1996. Dimensionless correlations for mixed and forced convection heat transfer to spherical and finite cylindrical particles in an aseptic processing holding tube simulator. J. Food Proc. Eng. 19 : 269-287.

Barbosa-Canovas, G. V., Pothakamury, U.R., Palou, E., Swanson, B.G. 1998. Nonthermal preservation of foods. Marcel Dekker, Inc., New York. 276pp.

Bean, E.C., Rasor, J.P., Porter, G.C. 1960. Changes in electrical conductivities of avocados during ripening. Year Book of California Avocado Soc. 44:75-78.

Begin, A., Beaulieu, Y., Goulet, J., Castaigne, F. 1995. Production of mycostatic whey by *Propionibacterium shermanii* immobilized in alginate gels. Milchwissenschaft 51(2):73-78.

Berry, M.F. 1989. Predicting the fastest residence time. First International Conference on Aseptic Processing Technologies. Indianapolis, IN, March 19-21.

Berry, M.F., Singh, R.K., Nelson, P.E. 1989. Kinetics of methylmethionine sulfonium in buffer solutions for estimating thermal treatment of liquid foods. J. Food Proc. Preserv. 13:475-488.

Berry, M.F., Singh, R.K., Nelson, P.E. 1990. Kinetics of methylmethionine sulphonium salt destruction in a model particulate system. J. Food Sci. 55:502-505.

Bhat, A., Joshi, V.K. 1998. Ohmic processing of foods, the concept, application, present status and future outlook. Alimentaria 289 : 83-88.

Bird, R.B., Stewart, W.E., Lightfoot, E.N. 1960. Transport phenomena. John Willey and Sons. New York.. 780 pp.

Biss, C.H. Coombes, S. A., Skudder, P.J. 1989. The development and Application of Ohmic Heating for the Continuous Heating of Particulate Foodstuffs *in:* « Process Engineering in the Food Industry ». Chap. 2: 17-26.

Box, G.E.P., Hunter, W.G., Hunter, J. S. 1978. Statistics for Experimenters. An Introduction to Design, Data Analysis and Model Building. Wiley-Interscience. 653pp.

Brown, K.L., Ayres, C.A., Gaze, J.E., Newman, M.E. 1984. Thermal destruction of bacterial spores immobilized in food/alginate particles. Food Microbiology 1:187-198.

Burgess, G.H.O., Cutting, C.L., Lovern, J.A., Waterman, J.J. 1967. Fish Handling and Processing. Chemical Publ. Co. New York. pp.182-194.

Burmeister, L.C. 1983. Convective heat transfer. Willey-Intersience Publication. John Willey and Sons. New York. 790 pp.

Bushnell, A.H., Dunn, J.E., Clark, R.W. 1991. High pulsed votage systems for extending the shelf life of pumpable food products. US Patent No. 5 048 404.

Castro, A.J., Barbosa-Canovas, Swanson, B.G. 1993. Microbial inactivation of foods by pulsed electric fields. J. Food Proc. Preserv. 17:47-73.

Chandarana, D.I., Gavin, A. III, Wheaton, F.W. 1988. Particle/fluid interface heat transfer during aseptic processing of food. ASAE Paper No. 88-6599. American Society of Agricultural Engineers. St. Joseph, MI.

Chen, A.C.-Y, Zahradnik, J.W. 1967. Residence-Time Distribution in a Swept-Surface Heat Exchanger. Transactions of ASAE 10(4):508-511.

Cho, H.-Y., Yousef, A.E., Sastry, S.K. 1996. Growth kinetics of *Lactobacillus acidophilus* under ohmic heating. Biotechnol. Bioeng. 49 : 334-340.

Christensen, S.H. 1982. Pectins *in*: « Food Hydrocolloids ». M. Glicksman ed. CRC Press Inc., Boca Raton, Florida, USA. Volume III. Chap. 9. Pp. 205-230.

Crow, D.R. 1979. Principles and Applications of Electrochemistry. 2nd edition. London Chapman and Hall chemistry textbook series. Johns Wiley and Sons. New York. 235pp.

Cuevas, R., Cheryan, M., Porter, V.L. 1982. Heat transfer and thermal process design in scraped surface heat exchangers. AICHE Symposium Series 78 : 49-57.

Cumming, W.G., Torrance, K. 1985. Chemical analysis - electrochemical techniques *in:* «Jones's Instrument Technology. Measurement of Temperature and Chemical Composition ». 4th edition. B.E. Noltingk ed. Butterworths, London. Volume 2. Chap. 4:105-143.

de Alwis, A.A.P., Fryer, P.J. 1988. Preliminary experiments on heat transfer during ohmic heating of foods *in* : « Proceedings of the 2nd UK National Heat Transfer Conference ». 1:229-239. Glasgow, I. Mech.E.

de Alwis, A.A.P., Halden, K., Fryer, P.J. 1989. Shape and Conductivity Effects in the Ohmic Heating of Foods. Chem. Eng. Res. Des. 67:159-168.

de Alwis, A.A.P., Fryer, P.J. 1990a. The Use of Direct Resistance Heating in the Food Industry. J. Food Eng. 11:3-27.

de Alwis, A.A.P., Fryer, P.J. 1990b. A finite-element analysis of heat generation and transfer during ohmic heating of food. Chem. Eng. Sci. 45(6):1547-1559.

de Alwis, A.A.P., Fryer, P.J. 1990c. The use of network theory in the finite-element analysis of coupled thermo-electric fields. Commun. Appl. Num. Methods 6:61-66.

de Alwis, A.A.P., Fryer, P.J. 1992. Operability of the Ohmic Heating Process: Electrical Conductivity Effects. J. Food Eng. 15:21-48.

Da Silva, J.A.L., Rao, M.A. 1995. Rheology of Structure Development in High-Methoxyl Pectin/Sugar Systems. Food Technol. 49(10):70-73.

Dallyn, H., Falloon, W.C., Bean, P.G. 1977. Method for the immobilization of bacterial spores in alginate gel. Lab. Pract. 26(10):773-775.

Damiano, D. 1997. Issues Involved in Producing a Multiphase Food Product. Food Technol. 51(10) : 56-62.

Danckwerts, P.V. 1953. Continuous flow systems. Chem. Eng. Sci. 2 (1):1-13.

Datta, A.K., Puckett, H.B., Spahr, S.L., Rodda, E.D. 1984. Real Time Acquisition and analysis of milk conductivity data. Trans. ASAE 27:1204-1210.

Davies, L.J., Kemp, M.R., Fryer, P.J. 1999. Use of computational models to study inhomogeneities in electrical field processing of foods. *Personal Communication.*

Dickerson, R.W. Jr., Scalzo, A.M., Read, R.B. Jr., Parker, R.W. 1968. Residence time of milk products in holding tubes of high-temperature short-time pasteurisers. J. Dairy Sci. 51 : 1731-1736.

Digeronimo, M., Garthright, W., Larkin, J.W. 1997. Statistical Design and Analysis. Food Technol. 51(10) :52-56.

Dignan, D.M., Berry, M.R., Pflug, I.J., Gardine, T.D. 1989. Safety Considerations in Establishing Aseptic Processes for Low-Acid Foods Containing Particulate. Food Technol. 43(3):118-121, 131.

Dunn, J.E., Pearlman, J.S. 1987. Methods and apparatus for extending the shelf life of fluid food products. US Patent No. 4 695 472.

Dutta, B., Sastry, S.K. 1990. Velocity Distributions of Food Particle Suspensions in Holding Tube Flow: Experimental and Modeling Studies on Average Particle Velocities. J. Food Sci. 55(5):1448-1453.

Dziezak, J.D. 1991. A Focus on Gums. Food Technol. 45(3):116, 118-120, 122-124, 126, 128, 130, 132.

Falkenhagen. H. 1934. Electrolytes (Oxford: Oxford University Press)

Fedorchenko, L.A., Gulyi, I.S., Bazhal, I.G., Bobrovnik, L.D., Karpovich, N.S., Zabrodskaya, E.A. and Martynenko, T.A. 1983. The effect of low voltage electric field on the electrical resistance of sugar beet tissue during the extraction proces. Sakharnaya Promyshlennost 2: 23-24.

Frampton. R. 1988. Ohmic potential. Food Manufacture 63(5): 61,63.

Fryer, P.J., de Alwis, A.A.P. 1989. The Validation of the APV Ohmic Heating Process. Chemistry and Industry Review 16:630-634.

Fryer, P., Li, Z. 1993. Electrical resistance heating of foods *in* : « Trends in Food Science and Technology ». Volume 4: 364-369.

Fryer, P.J., de Alwis, A.A.P., Koury, E., Stapley, A.G.F., Zhang, L. 1993. Ohmic Processing of Solid-Liquid Mixtures: Heat Generation and Convection Effects. J. Food Eng. 18:102-125.

Gaze, J.E. 1989. Application of an alginate particle technique to the study of particle sterilisation under dynamic flow, Technical Memorandum No. 547, The Campden Food and Drink Research Association. Chipping Campden, Gloucestershire, UK.

Gaze, J.E., Spence, L.E., Brown, G.D.,· Holdsworth, S.D. 1990. Microbiological assessment of process lethality using food/alginate particles. Technical Memorandum No.580. The Campden Food and Drink Research Association, Chipping Campden, Gloucestershire, UK.

Getchell, B.E. 1935. Electric pasteurization of milk. Agric. Engng. 16 : 408-410.

Giese, J. 1996. Commercial Development of Ohmic Heating Garners 1996 Industrial Achievement Award. Food Technol. 50(9), 114-115.

Glicksman, M. 1982a. Origins and classification of hydrocolloids *in* : « Food Hydrocolloids ». CRC Press Inc., Boca Raton, Florida. Volume 1, Chap. 1 : 3-18.

Glicksman, M. 1982b. Functional Properties of Hydrocolloids. *in* : « Food Hydrocolloids ». CRC Press Inc., Boca Raton, Florida. Volume 1, Chap. 3 : 47-99.

Glicksman, M. 1983. Red Swaweed Extracts (Agar, Carrageenans, Furcellaran) *in*: « Food Hydrocolloids ». M. Glicksman ed. CRC Press Inc., Boca Raton, Florida. Volume II, Chap. 5 : 73-113.

Grabowski, S., Ramaswamy, H.S. 1995a. Characterization of single particle tube-flow behavior at elevated temperatures. J. Food Proc. Eng. 18 : 343-361.

Grabowski, S., Ramaswamy, H.S. 1995b. Incipient velocity of carrier fluid in a holding tube of aseptic system. J. Food Eng. 24 : 123-136.

Grikitis, K. 1989. Shelf stable recipe dishes - a commercial reality. Food Processing UK 58(6):12-13.

Hahn, S.J., Ree, T., Eying, H.1959. Flow mechanism of thixotropic substances. Ind. Eng. Chem. 51 : 856-862.

Halden, K., de Alwis, A.A.P., Fryer, P.J. 1990. Changes in the electrical conductivity of foods during ohmic heating. Intl. J. Food Sci. Technol. 25:9-25.

Henderson, J.T. 1993. Ohmic Thawing of Frozen Shrimp : Preliminary Technical and Economic Feasibility. M.Sc. Thesis, University of Florida, Gainesville, FL.

Heppell, N.J. 1985. Comparison of the residence time distributions of water and milk in an experimental UHT steriliser. J. Food Process Eng. 4 : 71-84.

Hernandez, E. Chen, C.S. Johnson, J., Carter R.D. 1995. Viscosity changes in orange juice after ultrafiltration and evaporation. Elsevier Science Ltd. London. 387-395.

Hibberd, D. I. Howe, A. M. Mackie, A. R. Purdy, P. W., Robins, M.M. 1987. Measurements of creaming profiles in oil-in-water emulsions *in* : Food Emulsions and Foams ». E. Dickenson ed. The Royal Society of chemistry, London.

Holdsworth, S.D. 1971. Applicability of rheological models to interpretation of flow and processing behavior of fluid food products. J. Text. Stud. 2(4): 393-418.

Holdsworth, S.D., Richardson, P.S. 1989. Continuous Sterilization Operations for Aseptic Packaging : An Overview *in:* « Process Engineering in the Food Industry ». Chap. 1: 3-16.

Huang, L., Chen, Y., Morissey, M.T. 1997. Coagulation of fish proteins from frozen fish mince wash water by ohmic heating. J. Food Proc. Eng. 20 :285-300.

Huebner, K.H., Thornton, E.A. 1982. The Finite Element Method for Engineers. 2nd ed. John Willey and Sons Inc. New York.

Hulsheger, H., Potel, J., Niemann, E.G. 1983. Electric field effects on bacteria and yeast cells. Radiat. Env. Biophys. 22:149-162.

Hunter, G.M. 1972. Continuous sterilization of liquid media containing suspended particles. Food. Technol. Aust. 24:158-165.

Imai, T. K., Uemura, K., Ishida, K., Yoshizaki, S., Noguchi, A. 1995. Ohmic heating of Japanese white radish *Rhaphanus sativus* L. Int. J. of Food Sci. Technol. 30:461-472.

Imerson, A. 1992. Thickening and Gelling Agents for Food, 1st ed. Blackie Academic and Professional, Glasgow, Scotland.

Incropera, F.P., de Witt, D.P. 1990. Fundamentals of heat and mass transfer. Third Edition. John Wiley and Sons. New York. 919 pp.

Jason, A.C., Sanders, H.R. 1962a. Dielectric thawing of fish. I. Experiments with frozen herrings. Food Technol. 16(6) : 101-106.

Jason, A.C., Sanders, H.R. 1962b. Dielectric thawing of fish. II. Experiments with frozen white fish. Food Technol. 16(6) : 107-112.

Jayaram, S., Castle, J.S.P. 1992. Kinetics of sterilization of *Lactobacillus brevis* cells by the application of high voltage pulses. Biotech. and Bioeng. 40:1412-1420.

Jones, F. 1897. Apparatus for electricallly treating liquids. US Patent No. 1 592 735.

Jones, E.B. 1985. Chemical analysis - electrochemical techniques *in :* « Instrument Technology » 4th ed. Measurement of Temperature and Chemical Composition. B.E. Noltingk ed. Butterworths, London. Volume 2 Chap. 4:105-143.

Kelco. 1994. Xanthan gum Natural biogum for scientific water control. Fifth Edition.

Khalaf, W.G., Sastry, S.K. 1996. Effect of fluid viscosity on the ohmic heating rate of solid-liquid mixtures. J. Food Eng. 27:145-158.

Kim, H.J., Choi, Y.M., Yang, T.C.S., Taub, I.A., Tempest, P., Skudder, P., Tucker, G., Parrott, D.L. 1996a. Validation of Ohmic Heating for Quality Enhancement of Food Products. Food Technol. 50(5): 253-261.

Kim, H.J., Choi, Y.M., Yang, A.P.P., Yang, T.C.S., Taub, I.A., Giles, J., Ditusa, C., Chall, S., Zoltai, P. 1996b. Microbial and chemical investigation of ohmic heating of particulate foods using a 5 kW ohmic system. J. Food Proc. Preserv. 10 : 41-58.

King, K. 1991. Pectin : an untapped natural resource. Food Sci. Technol. Today 7(3): 147-152.

Kopelman, I.J. 1966. Transient heat transfer and thermal properties in food systems. *PhD thesis* (Michigan State Univ. East Lansing, MI.; cited by Heldman, D.R. and Singh. R.P. 1980. *Food Process Engineering* (AVI Publ. Co.; Division of Van Nostrand Reinhold, Westport, CT, USA.

Kulacki, F.A., Emara, A.A. 1977. Steady and transient thermal convection in a fluid layer with volumetric energy sources. J. Fluid Mechanics 83:375-395.

Kulacki, F.A., Nagle, M.E. 1975. Natural convection in a horizontal fluid layer with volumetric energy sources. J. Heat Transfer 91:204-211.

Lalande, M., Leuliet, J.C., Maingonnat, J.F. 1991. HTST processing of viscous liquid foods. *In:* "Processing and Quality of Foods, Vol. 1". P. Zeuthen et al. eds. Elsevier Applied Science, New York. pp.123-127.

Larkin, J.W. 1989. Use of a Modified Ball's Formula Method to Evaluate Aseptic Processing of Foods Containing Particulates. Food Technol. 43(3):124-131.

Larkin, J. W. 1997. Workships Targets Continuous Multiphase Aseptic Processing of Foods. Food Technol. 51(10) : 43-44.

Larkin, J.W., Spinak, S.H. 1996. Safety considerations for ohmically heated, aseptically processed, multiphase low-acid products. Food Technol. 50(5): 242-245.

Lee, J.H., Singh, R.K. 1990. Sensitivity analysis of aseptic process simulation for food containing particulate. J. Food Proc. Eng. 12:295-315.

Lee, J.J., Singh, R.K. 1991a. Process parameter effects on particle residence time in a vertical scraped surface heat exchanger. J. Food Sci. 56(3):869-870

Lee, J.H., Singh, R.K. 1991b. Particle residence time distributions in a model horizontal scraped surface heat exchanger. J. Food Proc. Eng. 14:125-146.

Lee, J.H.. Singh, R.K. 1991c. Residence time distribution characteristics of particle flow in a vertical scraped surface heat exchanger. J. Food Eng. 18:413-424.

Lee, J.H., Singh, R.K. 1993. Residence time distribution in a model horizontal scraped surface heat exchanger. J. Food Proc. Eng. 14:125-146.

Levespiel, O. 1972. Non–ideal flow *in:* "Chemical Reaction Engineering". 2nd Edition. John Willey and Sons. New York. pp. 253-32

Lin, S.H. 1979. Residence time distribution of flow in a continuous sterilisation process. Process Biochem. 20(7) : 23-27.

Liu, S., Pain, J.P., Fryer, P.J. 1992. The flow and velocity distributions of particles in liquids : application to food processing. Entropie 170 : 50-57.

Luzuriaga, D.E., Balaban, M.O. 1996. Electrical conductivity of frozen shrimp and flounder at different temperatures and voltage levels. J. Aquatic Food Product Technol. 5(3):41-63.

Manson, J.E., Cullen, J.F. 1974. Thermal process simulation for aseptic processing of foods containing discrete particulate matter. J. Food Sci. 39:1074-1089.

Marcy, J.E. 1997. Biological Validation. Food Technol. 51(10) : 48, 50, 52.

Marcotte, M., Ramaswamy, H.S. 1997. Rheology of Selected Food Thickening Agents in Solutions. Presented at the CIFST Conference. Paper 37. September 20-24. Montréal, Québec, Canada.

Marcotte, M., Ramaswamy, H.S. 1998. A Study on Electrical Conductivity of Hydrocolloid Solutions. Presented at the IFT Annual Meeting. Paper 33-2. June 20-24. Atlanta, Georgia, USA.

Marrs. W.M. 1996. Rheology as an Indicator of Functionality. The World of Ingredients. pp. 38-40.

Maxwell, J.C. 1954. A treatise on electricity and magnetism. Unabridged 3rd edition. Vol. 1 and 2. Part 2 Electrokinematics Dover publications Inc. USA.

McCoy, S.C., Zuritz, C.A., Sastry, S.K. 1987. Residence time distribution of simulated particles in a holding tube. ASAE Paper No. 87-6536.

Meredith, R.E., Tobias, C.W. 1961. Conductivities in emulsions. J. Electrochem. Soc. 108:286-290.

Mertens, B., Knorr, D. 1992. Developments of nonthermal processes for food preservation. Food Technol. 46(5):124-133.

Milton, J.L. and Zahradnik, J.W. (1973) Residence time distribution of a votator pilot plant using a non-Newtonian fluid. Transactions of ASAE 16(6):1186-1189.

Mitchell, E.L. 1987. A review of aseptic processing *in* : « Advances in Food Research » Vol. 32:1-37.

Mitchell, F.R.G., de Alwis, A.A.P. 1989. Electrical conductivity meter for food samples. J. Physics E: Scientific Instruments 22(8):554-556.

Mizhrahi, S., Kopelman, I.J., Perlman, J. 1975. Blanching by electro-conductive heating. J. Food Technol. (UK) 10:281-288.

Mizhrahi, S. 1996. Leaching of soluble solids during blanching of vegetables by ohmic heating. J. Food Eng. 29 : 153-166.

Moses, D.B., 1938. Electric pasteurization of milk. Agric. Engng. 19 : 525-526.

Mudget, R.E. 1992. Electrical properties of foods *in* : « Engineering properties of Foods ». M.A. Rao, S.S.H. Rizvi eds. 2nd ed. Marcel Dekker Inc. New York. Chap. 8: 389-455.

Muller, F.L., Pain, J.P., Villon, P. 1994. On the Behaviour of Non-Newtonian Liquids in Collinear Ohmic Heaters *in:* « Proceedings of the Tenth International Heat Transfer

Conference ». Volume 4 Freezing, melting, internal forced convection and heat exchangers. Brighton, UK. pp. 285-290.

Mulley, E.A., Stumbo, C.R., Hunting, W.A. 1975. Thiamine: A chemical index of sterilization efficacy of thermal processing. J. Food Sci. 40:993-996.

Murakami., E.G., Okos., M.R. 1989. Measurement and prediction of thermal properties of foods *in:* Proceedings of a NATO advanced research workshop on "Food properties and computer-aided engineering of food processing systems". Universidade Catolica Portuguesa. Portugal.

Naveh, D., Kopelman, I.J., Mizrahi, S. 1983. Electroconductive thawing by liquid contact. J. Food Technol. 10 : 282-288.

Ohashi, H., Sugawara, T., Kikuchi, K.-I., Isé, M. 1990. Average particle velocity in solid-liquid two-phase flow through vertical and horizontal tubes. J. Chem. Eng. Japan 13(5):343-349.

Ohtsuki, T. 1990. Process for thawing foodstuffs. US Patent No. 5 034 236.

Orangi, S., Sastry, S.K. 1998. A numerical investigation of electroconductive heating in solid-liquid mixtures. Intl. J. Heat Mass Transfer 41(14) : 2211-2220.

Pain, J.P., Baudez, P. 1994. Le chauffage ohmique : un procédé industriel UHT. Les cahiers de l'ingénierie 52(6): 10-16.

Pain, J.P., Dornier, M., Baudez, P. 1995. Le chauffage ohmique : Innovation industrielle pour le traitement UHT des produits particulaires. Actualités techniques et industrielles. Industries Agricoles et Alimentaires (IAA). Juin. pp. 405-410.

Palaniappan, S., Sastry, S.K. 1990. Effects of electricity on microorganisms: A review. J. Food Proc. Preserv. 14:393-414.

Palaniappan, S., Sastry, S.K. 1991a. Electrical conductivities of selected solid foods during ohmic heating. J. Food Proc. Eng. 14:221-236.

Palaniappan, S., Sastry, S.K. 1991b. Electrical conductivity of selected juices: Influences of temperature, solids content, applied voltage, and particle size. J. Food Proc. Eng. 14:247-260.

Palaniappan, S., Sastry, S.K. 1991c. Modelling of electrical conductivity of liquid-particle mixtures. Food and Bioproducts Proc., Trans. Inst. Chem. Eng. Part C 69:167-174.

Palaniappan, S., Sastry, S.K. and Richter, E.R. 1992. Effects of Electroconductive Heat Treatment and Electrical Pretreatment on Thermal Death Kinetics of Selected Microorganisms. Biotechnol. Bioeng. 39:225-232.

Palaniappan, S., Sizer, C.E. 1997. Aseptic Process Validated for Foods Containing Particulates. Food Technol. 51(8) : 60-68.

Palmer, J.A., Jones, V.A. 1976. Prediction of holding times for continuous thermal processing of power law fluids. J. Food Sci. 41:1233-1244.

Palmieri, L., Cacace, D., Dipollina, G., Dall'Aglio, G. 1992. Residence time distribution of food suspensions containing large particles when flowing in tubular systems. J. Food Eng. 17:225-239.

Park, S.J., Kim, D., Uemura, K., Noguchi, A. 1995. Influence of frequency on ohmic heating of fish protein gel. Nippon Shokuhin Kagaku Kogaku Kaishi 42(8) : 569-574.

Parrot, D.L. 1992. Use of ohmic heating for aseptic processing of food particulate. Food Technol. 46(2):68-72.

Peyron, A. 1996. Perspectives et développement de nouvelles techniques de cuisson des viandes. Viandes Prod. Carnés 17(6) : 255-262.

Pflug, I.J., Berry, M.R., Dignan, D.M. 1990. Establishing the heat preservation process for aseptically-packaged low-acid food containing large particulate, sterilized in a continuous heat-hold-cool system. J. Food Protect. 53(4):312-321.

Piette, J.P.G., Jacques, L.1997 Evaluaton of a rapid fat analyzer, based on ohmic heating, for the classification of ground beef. Fleischwirtschaft 77(1) : 54-56.

Plackett, R.L., Burman, J.P. 1946. The Design of Optimium Multifactorial Experiments. Biometrika 33:305-325.

Pothakamury, U.R., Barbosa-Canovas, G.V., Swanson, B.G. 1993. Magnetic field inactivation of microorganims and generation of biological changes. Food Technol 47(12): 85-91.

Przybyla, A. E. 1987. Calorie reduction achieved with help of Stabilizers. Food Eng. 59(1): 60-66.

Qihua, T., Jindal, V.K., van Winden, J. 1993. Design and performance evaluation of an ohmic heating unit for liquid foods. Computers and Electronics in Agriculture 9 : 243-253.

Quarini, G.L. 1995. Thermalhydraulic Aspects of the Ohmic Heating Process. J. Food Eng. 24: 561-574.

Rahman, S. 1995a. Thermal conductivity of foods *in* : « Food Properties Handbook ». CRC Press Inc., London. Chap. 5. Pp. 275-336.

Rahman, S. 1995b. Specific heat, enthalpy and latent heat of food *in* : « Food Properties Handbook ». CRC Press Inc., London. Chap. 4. Pp. 225-271.

Ramaswamy, H.S., Basak, S. 1991. Rheology of stirred yogurt. J. Texture Stud. 22:231-241.

Ramaswamy, H.S., Basak, S. 1992. Time Dependent Stress Decay Rheology of Stirred Yogurt. Int. Dairy J. 1:17-31.

Ramaswamy, H.S., Abdelrahim, K.A., Marcotte, M., Clavier, P. 1995a. Residence time distribution (RTD) characteristics of meat and carrot cubes in starch solutions in a vertical scraped surface heat exchanger (SSHE). Food Res. Intl. 28(3):273-284.

Ramaswamy, H.S., Abdelrahim, K.A., Simpson, B.K., Smith, J.P. 1995b. Residence time distribution (RTD) in aseptic processing of particulate foods : a review. Food Res. Intl. 28(3) : 291-310.

Ramaswamy, H.S., Grabowski, S. 1998. Identification of fastest velocity particle in tube flow : Single vs multi-particle approach – Hypothesis Paper. J. Food Sci. 63 : 565-570.

Rao, M.A. 1977. Rheology of liquid foods - A review. Journal of Texture Stud. 8:135-168.

Rao, M.A. 1986. Rheological properties of fluid foods *in:* "Engineering Properties of Foods". M.A. Rao and S.S.H. Rizvi eds. Marcel Dekker. New York. pp.1-47.

Rao, M.A. 1992. Rheology of fluids in food processing. Food Technol. 46 (2): 116-126.

Rao, M.A., Anantheswaran, R.C. 1982. Rheology of fluids in food processing. Food Technol. 36 (2): 116-126.

Rao, M.A., Loncin, M. 1974. Residence time distribution and its role in continuous pasteurisation (Part II). Lebensm.-Wiss. u. –Technol. 7 : 14-17.

Rao, M.A., Kenny, J.F. 1975. Flow properties of selected food gums. Can. Inst. Food Sci. Technol. J. 8(3):142-148.

Remik, D. 1988. Apparatus and method for electrical heating of food products. US Patent No. 4 739 140.

Reznick, D. 1996. Ohmic Heating of Fluid Foods. Food Technol. 50(5):250-251.

Rha, C. 1978. Rheology of fluid foods. Food Techol. 32(7) :77-82.

Rice, J. 1995. Ohmic Adventures. Food Processing (March) : 89-91.

Roberts, J.S., Balaban, M.O., Zimmerman, R., Luzuriaga, D. 1998. Design and testing of a propotype ohmic thawing unit. Computers and Electronics in Agriculture 19 : 211-222.

Rosett, T.R., Kendregan, S.L., Gao, Y., Schmidt, S. J., Klein, B.P. 1996. Thickening agents effects on sodium binding and other taste qualities of soup systems. J. Food Sci. 61(5):1099-1104.

Russell, A.D. 1982. The destruction of bacterial spores. Academic Press, London, New-York.

Sancho, M.F., Rao, M.A. 1992. Residence time distribution in a holding tube. J. Food Eng. 15 : 1-19.

Sanders, H.R. 1963. Electrical resistance thawing of fish. *in :* « Annual Report on the Handling and Preservation of Fish and Fish Products » Torry Memoir No. 143. Torry Research Station, Aberdeen, Scotland, pp. 16-17.

Sanderson G. R. 1981. Polysaccharides in food. Food Technol. 7(4):50-56.

Sanderson. G.R. 1996. Gums and their use in food systems. Food Technol. 50(3):81-84.

Sasson, A., Monselise, S.P. 1977. Electrical conductivity of 'Shamouti' orange peel during fruit growth and postharvest senescence. Amer. Soc. Hort. Sci. J. 102(2):142-144.

Sastry, S.K., Li, S.F., Patel, P., Konanayakam. M., Bafna, P., Doores, S., Beelman, R.B. 1988. A bioindicator for verification of thermal processes for particulate foods, J. Food Sci. 53(5): 1528-1536.

Sastry, S.K., Lima, M., Brim, J., Brunn, T., Heskitt, B.F. 1990. Liquid-to-particle heat transfer during continuous tube flow: influence of flow rate and particle to tube diameter ratio. J. Food Proc. Eng. 13: 239-253.

Sastry, S.K. 1991. Ohmic sterilization and related safety issues. International Winter meeting of ASAE. Paper 916616.

Sastry, S.K. 1992a. A model for heating of liquid-particle mixtures in a continuous flow ohmic heater. J. Food Proc. Eng. 15:263-278.

Sastry, S.K. 1992b. Modelling the continuous sterilization of particulate foods *in :* « Mathematical Modelling of Food Processing Operations ». S. Thorne ed. Elsevier Applied Food Science Series. USA. Chap. 6:233-270.

Sastry, S.K. 1992c. Advances in ohmic heating for sterilization of liquid particle mixtures *in :* « Advances in Food Engineering ». R.P. Singh & Wirakartakusumah eds. CRC Press. USA. Chap. 11:139-148.

Sastry, S. K. 1997. Measuring residence time and modeling the system. Food Technol. 51(10) :44-48.

Sastry, S.K., Li, Q. 1993. Models for ohmic heating of solid-liquid food mixtures *in:* «Heat Transfer in Food Processing». Presented at the 29th National Heat Transfer Conference of the American Society of Mechanical Engineers (ASME), Atlanta, Georgia, August 8-11, Volume 254:25-33.

Sastry, S.K., Li, Q. 1996. Modeling the ohmic heating of foods. Food Technol. 50(5): 246-248.

Sastry, S.K., Palaniappan, S. 1992a. Ohmic heating of liquid-particle mixtures. Food Technol. 46(12):64-67.

Sastry, S.K., Palaniappan, S. 1992b. Influence of particle orientation on the effective electrical resistance and ohmic heating rate of a liquid-particle mixture. J. Food Proc. Eng. 15:213-227.

Sastry, S.K., Palaniappan, S. 1992c. Mathematical modeling and experimental studies on ohmic heating of liquid-particle mixtures in a static heater. J. Food Proc. Eng. 15:241-261.

Sastry, S.K., Salengke, S. 1998. Ohmic heating of solid-liquid mixtures : a comparison of mathematical models under worst-case heating conditions. J. Food Proc. Eng. 21: 441-458.

Scalzo, A.M., Dickerson, R.W. Jr., Read, R.B. Jr., Parker, R.W. 1969. Residence time of egg products in holding tubes of egg pasteurisers. Food Technol. 23 : 80-83.

Schade, A.L. 1951. Prevention of enzymatic discoloration of potatoes. US Patent No. 2 569 075.

Scott-Blair, G.W. 1969. Elementary Rheology. Academic Press Inc. New-York.

Segner, W.P., Ragusa, T.J., Marcus, C.L., Soutter, E.A. 1989. Biological evaluation of a heat transfer simulation for sterilizing low-acid large particulate foods for aseptic packaging. J. Food Preserv. 13:257-274.

Simpson, D.P. 1980. Apparatus for heating electrically conductive flowable media. UK Patent No. 2 067 390.

Simpson, D.P. 1983. Apparatus for heating electrically conductive flowable media. US Patent No. 4 417 132.

Skudder, P. J., Biss, C. 1987. Aseptic processing of food products using ohmic heating. Chem. Eng. 433:26-28.

Skudder, P.J. 1988. Development of the ohmic heating process for continuous sterilisation of particulate food products *in :* « Proceeding international symposium on progress in food preservation » 1:271-280.

Skudder, P.J. 1991. Industrial application of the ohmic heater for the production of high-added value food products. Proceedings of the VTT Symposium No.19 Technical Research. Center of Finland Espoo 15. pp. 47-52.

Smith, J.P., Ramaswamy, H.S., Simpson, B.K., 1990. Developments in food packaging technology. Part 1. Processing/cooking considerations. Trends Food Sci. Technol. 1(5) : 106-109.

Speers, R.A., Tung, M.A. 1986. Concentration and temperature dependence of flow behavior of xanthan gum dispersions. J. Food Sci. 51(1): 96-98, 103.

Sperber, B. 1992. Ohmic - a shock to the system. Food Processing (November) : 97-99.

Steffe, J.F. 1992. Rheological methods in food process engineering. Freeman Press, East Lansing Michigan.

Stirling, R. 1987. Ohmic heating-a new process for the food industry. Power Eng. J. 6:365-371.

Sweat, V.E., Haugh, C.G., Stadelman, W.J. 1974. Experimental values of selected fruits and vegetables. J. Food Sci. 39:1080-1083.

Swientek, R.J. 1988. Aseptically processes particulates without mechanical agitation. Food Processing USA. 49(1): 42,44.

Szczesniak, A. S. 1985. Rheological basis for selecting hydrocolloids for specific applications *in:* « Gums and Stabilizers for the Food Industry ». Pp.311-323. G.O. Phillips, D.J. Wedlock, P.A. Williams eds., Elsevier Applied Science Publishers, London.

Taffe, P. 1987. Ohmic heating sparks off new possibilities. Processing (October) : 41-42.

Taguchi, G. 1987. System of experimental design. Engineering methods to optimize quality and minimize costs. Vol. 1 & 2. Don Clausing Technical ed. UNIPUB/Kraus International Publications. 1177pp.

Tjomb, P. 1995. Chauffage ohmique : le CTCPA operationnel. Revue Industrielle Agroalimentaire (RIA) 542: 53-55.

Toda, M., Ishikawa, T., Saito, S. Maeda, S. 1973. On the particle velocities in solid-liquid two-phase flow. J. Chem. Eng. Japan 6 : 140-146.

Toda, M., Yonehara, J., Kimura, T., Maeda, S. 1979. Transition velocities in horizontal solide-liquid two-phase flow. Intl. Chem. Eng. 19(1):145-152.

Tsong, T.Y. 1990. Review : On electroporation of cell membranes and some related phenomena. Bioelectrochem. Bioenergetics. 24 : 271-295.

Tucker, G.S., Richardson, P.S. 1989. Residence time distribution and flow behaviour of foods containing particles in aseptic processing. Paper presented at the AIChemE Conference of Food Engineering (COFE 3), Chicago, Februay 21-24.

Tucker, G.S., Withers, P.M. 1992. Determination of residence time distribution of food particles in viscous food carrier fluids using Hall effect sensors. Technical Memorandum No. 667. Campden Food and Drink Research Association. Gloucestershire. UK.

Turian, R.M. 1964. Thermal phenomena and non-Newtonian viscometry. Ph. D. Thesis. Univ. of Wisconsin, Madison.

Uemura, K., Noguchi, A. 1995. Ohmic heating of food materials its principle and application effects of frequency on the heating rate of fish protein. *Personal Communication.*

Uemura, K., Isobe, S., Imai, T., Noguchi, A. 1996a. Estimation of temperature profile at ohmic heating by finite element method. Nippon Shokuhin Kagaku Kogaku Kaishi 43(5) : 510-519.

Uemura, K., Isobe, S., Noguchi, A. 1996b. Analysis, using finite element method, of the temperature distribution in continuous ohmic heating. Nippon Shokuhin Kagaku Kogaku Kaishi 43(11) : 1190-1196.

Valentas, K.J., Levine, L., Clark, J.P. 1991. Food Processing Operations and Scale-up. Marcel Dekker Inc., New York.

Wang, W.-C., Sastry, S.K. 1993. Salt diffusion into vegetable tissue as a pretreatment for ohmic heating : electrical conductivity profiles and vacuum infusion studies. J. Food Eng. 20 :299-309.

Wang, W.-C., Sastry, S.K. 1997a. Changes in electrical conductivity of selected vegetables during multiple thermal treatments. J. Food Proc. Eng. 20:499-516.

Wang, W.-C., Sastry, S.K. 1997b. Starch Gelatinization in Ohmic Heating. J. Food Eng. 34:225-242.

Weaver, G.M., Jackson, H.O. 1966. Electrical impedance an objective index of maturity in peach. Can. J. Plant. Sci. 46:323-326.

Weltmann, R.N. 1943. Breakdown of thixotropic structure as function of time. J. Appl. Physics. 14:343-350.

Weng, W.M., Hendrickx, M., Maesmans, G., Tobback, P., 1991. Immobilized peroxidase: a potential bio-indicator for evaluation of thermal processes. J. Food Sci. 56:567-570.

Wigerstrom, K.B. 1976. Method and device for preparing foodstuffs with direct passage of electric current. US Patent No. 3 996 385.

Woodroff, J.G. 1990. 50 years of fruits and vegetables processing. Food Technol. 44(2):92-96.

Yang, B.B., Swartzel, K.R. 1991. Photo-sensor Methodology for Determining Residence Time Distributions of Particles in Continuous Flow Thermal Processing Systems. J. Food Sci. 56(4):1076-1081, 1086.

Yang, B.B., Swartzel, K.R. 1992. Particle Residence Time Distributions in Two-phase Flow in Straight Round Circuit. J. Food Sci. 57(2): 497-502.

Yilmazer, G., Kokini, J.L. 1992. Effect of salt on the stability of propylene glycolalginate/xanthan gum/polysorbate-60 stabilized oil-in-water emulsions. J. of Text. Stud. 23: 195-213.

Yongsawatdigul, J., Park, J.W., Kolbe, E., Abu Dagga, Y., Morissey, M.T. 1995a. Ohmic heating maximizes gel functionality of pacific whiting surimi. J. Food Sci. 60(1) :10-14.

Yongsawatdigul, J., Park, J.W., Kolbe, E. 1995b. Electrical conductivity of Pacific Whiting surimi paste during ohmic heating. J. Food Sci. 60(5):922-925,935.

Zaror, C.A., Pyle, D.L., Molnar, G. 1993. Mathematical modelling of an ohmic heating steriliser. J. Food Eng. 19 : 33-53.

Zhang, L., Liu, S., Pain, J.P., Fryer, P.J. 1992. Heat transfer and flow of particle-liquid food mixtures. IChemE Symp. Ser. 126: 79-88.

Zhang, L., Fryer, P.J. 1993. Models for the electrical heating of solid-liquid food mixtures. Chem. Eng. Sci. 48(4) : 633-642.

Zhang, L., Fryer, P.J. 1995. A Comparison of alternative formulations for the prediction of electrical heating rates of solid-liquid food materials. J. Food Proc. Eng. 18:85-97.

Zitoun, K.B., Sastry, S.K. 1994a. Determination of convective heat transfer coefficient between fluid and cubic particles in continuous tube flow using noninvasive experimental techniques. J. Food Proc. Eng. 17:209-228.

Zitoun, K. B., Sastry, S.K. 1994b. Convection heat transfer coefficient for cubic particles in continuous tube flow using the moving thermocouple method. J. Food Proc. Eng. 17:229-241.

Zlokarnik, M. 1991. Dimensional analysis and scale-up in chemical engineering. Springer Verlag, Berlin.

Zoltai, P. and Swearingen, P. 1996. Product development considerations for ohmic processing. Food Technol. 50(5):263-266.

Zuber, F. 1997. Le chauffage ohmique : Une nouvelle technologie pour la stabilisation des plats cuisinés. Viandes Prod. Carnés 18(2) : 91-95.

Zuritz, C.A., McCoy, S., Sastry, S.K. 1990. Convection heat transfer coefficients for irregular particles immersed in non-newtonian fluid during tube flow. J. Food Eng. 11:159-174.