COMPARISON OF QUALITY CHANGE KINETICS IN HAM EMULSIONS COOKED UNDER CONVENTIONAL AND OHMIC HEATING CONDITIONS

by

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OHMIC HEATING OF HAM EMULSION

DEDICATION

This thesis is dedicated to all peoples of all nations. Recognizing that hunger, malnutrition, poverty and illiteracy are the root of the world's problems, it is the fervent hope of me that this thesis will help to resolve this universal dilemma and contribute in some way to aiding greater global understanding and world peace and prosperity.

It is not what we give, but what we share,
The gift without the giver is bare;
Who gives himself with his alms feeds three,
Himself, his hungering neighbor, and me.

(James Russell Lowell)

ABSTRACT

Traditional cooking of comminuted meat products in smokehouses is generally long, taking up to 12 hours for large-size products like ham or bologna. Rapid heating techniques are continuously being explored as alternatives to traditional cooking. Ohmic heating is one of these rapid heating methods, which could have interesting applications for the prepared meat industry. Ohmic heating is an electrical resistance heating resulting from the passage of electrical current through an electrically conductive material offering some resistance. Most food products possess sufficient electrical conductivity to be able to take advantage of ohmic heating. This research was undertaken to evaluate the quality changes associated with fine ham emulsions prepared under ohmic heating conditions as compared to those produced by conventional heating.

In the first part of the study, kinetics of quality changes (color, texture, water holding capacity, cooking loss and water activity) associated with fine ham emulsion subjected to conventional heating conditions were evaluated. Samples of raw fine ham emulsion (~30g), prepared according to an industry standard formulation, were sealed in transparent plastic tubes and subjected to conventional heat treatments in a well agitated water bath at selected temperatures (50, 55, 60, 65, 70, 75, and 80°C) yielding a range of holding times after the target temperature is reached. Results showed that higher process temperatures and longer heating times caused faster color and texture development. At lower temperatures ($\leq$65°C), color and texture development was completed only during the holding period while at higher temperatures (>70°C) they reached their full extent by the end of come-up period. Thus, color and texture development were dependent on both bath temperature and heating time.

The second part of the study was to standardize ohmic heating conditions for achieving target time-temperature combinations. It was desired to achieve cooking conditions (temperature come-up and hold times) both similar to and faster than conventional heating so that meaningful quality comparisons could be made between the two. Since ohmic heating rates depended on product and system characteristics, this research was necessary to standardize the heating conditions. The product composition was kept the same and a sample size of 1 kg was used in a static ohmic heating cell. From the time-temperature and voltage data, heating rates achieved through ohmic heating were evaluated and modelled. Data on electrical conductivity associated with the ham emulsions were also computed form the measured time-temperature-voltage data. Results showed that electrical conductivity increased linearly with increasing temperature.

The final part of the study was to compare the quality changes of fine ham emulsion subjected to ohmic heating under different rates, and to compare them with conventional heating. Cooking temperature and come-up time significantly ($p<0.05$) influenced the color and texture of test samples subjected to ohmic heating conditions, higher temperatures, shorter come-up times and longer holding times showing lighter color and softer texture. Furthermore, as compared to the conventionally cooked product, ham emulsions cooked under ohmic heating had a lighter and more red color, softer and chewier texture ($p<0.05$). The quality improvement under ohmic heating as compared to the conventional heating is

likely due to the rapid heating rates associated with the ohmic heating. In addition, ohmic heating can reduce the cooking time by more than 75%, even for larger samples, which could result in better production rates.

RÉSUMÉ

La cuisson traditionnelle des produits de la viande dans les fumoirs est généralement longue, pouvant prendre jusqu'à 12 heures pour de gros produits tel le jambon ou le saucisson de bologne. Les techniques de cuisson rapides sont continuellement à l'étude afin de trouver une alternative à la cuisson traditionnelle. Le chauffage ohmique est l'une de ces méthodes rapide, qui pourrait avoir des applications interessantes pour l'industrie des viandes préparées.

La cuisson ohmique est le résultat d'un chauffage dû au passage d'un courrant électrique à travers un matériau conducteur qui offre une certaine résistance. La plupart des produits alimentaires possèdent une conductivité électrique suffisante pour pouvoir prendre avantage du chauffage ohmique. Cette recherche fût entreprise dans la but d'évaluer la qualité des changements associée au émulsions des jambons fins préparés sous des conditions de chauffage ohmique comparativement à ceux préparés utilisant les conditions de cuisson traditionnelle.

Dans la première partie de cette étude, les changements cinetiques de la qualité (couleur, texture, capacité de retenu d'eau, pertes dûe à la cuisson et activité de l'eau) associés à l'émulsion du jambon fin assujeti aux conditions de rechauffement conventionels furent évalués. Des échantillons d'émulsion de jambon fin crû (approximativement 30gr), préparés suivant les normes formulées de l'industrie, fûrent scellés dans des tubes de plastique transparent et soumis au traitement de cuisson conventionnel dans un bain d'eau bien agitée (50, 55, 60,

65, 70, 75 et 80 degrés Celcius) résultant en un rayon de temps de retenu apr`s que la température désirée soit atteinte.

Les résultats démontrèrent les procédés à plus hautes température et temps de retenu plus longs causèrent le dévelopement plus rapide de la couleur et de la texture. À des températures plus basses (≤65°C), le dévelopement de la couleur et de la texture fût complété seulement durant les périodes de retenue, tandis qu'à des températures plus hautes (>70°C) elles atteignèrent de pleins résultats à la fin de la période de retrait. Donc le dévelopement de la couleur et de la température dépendirent et de la température du bain et du temps de cuisson.

La deuxième partie de l'étude consitèrent à normaliser les conditions de chauffage omique dans le but d'obtenir les combinaisons temps-température désirées. Nous souhaitions obtenir des conditions de cuisson (température de sortie et temps de retenu) similaires et plus rapides que la cuissson conventionelle de sorte que des comparaisons de qualité valables puissent être faites entre les deux. Comme le ratio de chauffage ohmique dépend du produit et des caractéristiques du système, cette recherche fût nécessaire afin de normaliser les condition de chauffage. La composition du produit fût gardée la même et un échantillon de 1kg fût utilisé dans une cellule de chauffage ohmique statique.

À partir des donnés temps-température et de la tension électrique, les temps de traitement à chauffage ohmique requis pour obtenir les rapport de chauffage désirés fûrent évalués et un modèle fût établi. Les donnés sur la conductivité électrique associées au émulsions de jambon fûrent aussi calculées à partir des donnés temps-température-tension. Les résultats démontrèrent que la

conductivité électrique augmente de façon linéaire avec l'augmentation de la température.

La dernière partie l'etude consita à comparer les changements de la qualité des émulsions du jambon fin assujeti au chauffage ohmique à différent taux de réchauffement et de les comparer au chauffage traditionnel. Les températures de cuisson et temps de sortie influencèrent de façon significative ($p>0.05$) la couleur et la texture des échantillons de vérification assujeties aux conditions de chauffage ohmique, plus hautes températures, temps moindre de sortie et temps accrù de retenu donnant des couleurs plus pâles et une texture plus molle. De plus, lorsque comparées aux produits cuits selon les méthodes de cuisson conventionelles, les émulsions de jambon cuit sous la methode de chauffage ohmique avaient une couleur plus rouge, une texture plus molle et moins consitente (chewy) ($p<0.05$). L'amélioration de la qualité sous le chauffage ohmique comparativement à la méthode conventionelle est probablement causée par le taux rapide de chauffage associé au chauffage ohmique. De plus, le chauffage ohmique peut réduire le temps de cuisson par plus de 75%, même pour les échentillons plus gros, ce qui pourrait avoir comme résultat de meilleurs taux de production.

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NOMENCLATURE

a_w	water activity
A	surface area (cm^2)
C	concentration (% w/w)
C	cooking value
C_p	specific heat (J/kg-°C)
CUT	come-up time
cm	centimeter
D	decimal reduction time, negative reciprocal slope of the semi-logarithmic D-value curve
ρ	delta
E	voltage gradient or local electric field intensity (V/cm)
E_a	activation energy (kJ/mole)
g	gram
h	hour
I	current (A)
Hz	hertz
k	reaction rate constant at T (°C)
k_o	frequency factor
K_S	solid constant (1/%)
K_T	temperature constant (S/m °C)
kg	kilogram
L	distance between electrodes (cm)

m	mass flow rate (kg/s)
N	microbial count
n	reaction order
p	hydrostatic pressure (Pa)
P	power (W)
Q	volumetric heat generation (W/m^3)
R	resistance (ohm)
RT	residence time (s)
R	gas constant (8.3184 x 10^{-3} kJ/mole K)
ρ	density (kg/m^3)
S	surface (m^2)
Slope	slope of a linear equation
σ	Electrical conductivity (S/m or 1/ohm*m)
t	time (min)
T	temperature (^{o}C)
t_e	effective heating time
V	voltage (V)
∇V	voltage gradient (V/m)
W	mass (g or kg)
Z	negative reciprocal slope of the semi-logarithmic z-value curve

Subscripts

0	initial

C	concentration
max	maximum
min	minimum
T	temperature
out	outlet
ref	reference
w	water

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- Chiu, L., Ramaswamy, H.S., Piette, G, Koutchma, T. Evaluation of color formation kinetics during cooking of ham emulsions, Presented at the International Congress for Engineering and Food, Puebla, Mexico, April 9-13, 2000. Poster presentation.

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CHAPTER 1

INTRODUCTION

Current trends indicate an ever increasing use of comminuted meat products, such as frankfurters, sausages, luncheon meat and ham in the North American diet. From 1979 to 1989, the changes in consumer expenditures for meat increased 26% (Pearson and Gillett, 1996). Due to changing lifestyles, demographics and the increasing number of multiple-income families, today's consumers have more demand for convenient, safe and high quality food products. An increase in disposable income and time restrictions for meal preparation are becoming leading factors for the growing popularity of processed foods on the market, and this trend is more than likely to continue into 21st century. Consumers favor sausage products because they are convenient to prepare and serve, palatable and flavorful, attractive, and economical, and they add variety to the menu.

Traditional cooking, of comminuted meat products in "smoke chambers" is generally long, taking up to 12 hours for large scale products like ham or Bologna, and this may have two undesirable consequences. First, cooking process requires considerable amount of energy because of the need to maintain elevated temperatures for several hours. Secondly, the long cycle of cooking imply immobilization of huge quantities of products for prolonged periods, lowering considerably the rate (flow) of production. The introduction of continuous cooking, now being adapted in smoked-sausage plants, has allowed to partially correct the low flow of production, but cannot be easily applied to large pieces of meat because of the slow heating of the product.

In this context, it is evident that faster methods of cooking would allow considerable energy savings, while raising the production rate. Direct immersion in heated water baths could be an alternative. 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 lower production rate and time consuming cooking 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. Ohmic heating rates are critically dependent on the electrical conductivity of the food (Parrott, 1992).

The concept of Ohmic heating of foods is not new. In the 19th century, several processes used electrical energy for heating flowable materials. In the early 20th century, "electric pasteurization of milk was achieved by passing milk between parallel plates with a voltage difference between them. It was thought at the time that lethal effects could be attributed to electricity. The technology slowly disappeared in succeeding years, its failure being apparently due to lack of suitable inert electrode material and controls. Within the past few decades, APV Baker Ltd, UK and UK Electricity Council Research Center developed new and improved materials and design for Ohmic heating to enable the food processing industry to produce value-added products with major improvements in structural, nutritional and organoleptic properties.

There are several advantages associated with Ohmic heating (Biss *et al.*, 1989; Skudder and Biss, 1987). Ohmic heating is uniform, rapid, and with a larger heat penetration depth compared to other heating techniques. The Ohmic heating rate is calculated from the electric field strength, the electrical conductivity, the density and the specific heat of the food product. Therefore, the heating rate depends largely on the physical characteristics of the food itself, especially on the electrical conductivity (de Alwis and Fryer, 1992). It is possible to apply Ohmic heating to comminuted meat emulsion production because the product contains dissolved ionic salts and water which make them electrically conductive. However, pure lipids, protein and carbohydrate are not good candidates for Ohmic heating. These substances do not contain sufficient electrical conductive materials, i.e. ionic salts. The electrically conductivity of comminuted meat emulsion depends on the AC voltage frequency and temperature. As either temperature or voltage increases, electrical conductivity increases.

Available information on Ohmic heating characteristics of food products is rather limited and as related to comminuted ham emulsions, it is quite scarce. Hence the following objectives were adapted for the thesis:

1. To study kinetic changes in quality of fine ham emulsion under conventional water bath heating conditions

2. To evaluate the Ohmic heating behavior and electrical conductivity of fine ham emulsions and to standardize the Ohmic heating conditions for prepared ham emulsions
3. To compare the quality of ham emulsion cooked under different conventional and Ohmic heating conditions

CHAPTER 2

LITERATURE REVIEW

2.1. THERMAL PROCESSING

Since Nicholas Appert's invention in the late 19th century for food preservation such as meat, vegetables, fruit and milk heated in carefully corked glass bottles, thermal processing or canning, has gone through tremendous transformations both in the processing techniques and equipment development. His invention of the heat preservation technique is also known as "Apperization". Even though at the time the reason for the principle of heat sterilization was unknown, Appert learned that it was necessary to distinguish between acid foods and non-acid foods in terms of how long they should be processed (Ball, 1938). Appert also noted that improvement of the quality of these processed foods was one of the primary incentives which led to discovery of heat sterilization.

Heat has important influences on food processing in several respects: it is the most convenient method to extend the shelf life of foods by destroying enzymatic and microbiological activity, or by removing water to inhibit deterioration; and it improves the nutritional and sensory qualities of many foods. Manufacturers have relied on conventional heat exchange technology to pasteurize and sterilize food in an attempt to kill harmful viruses and microorganisms such as *Salmonella* and *Listeria.*

The term *thermal processing* is used in a general sense and relates to the determination of heating conditions required to produced microbiologically safe products of acceptable eating quality (Holdsworth, 1997).

Food processing involves the transfer of heat into a food. There are three ways in which heat may be transferred: conduction, convection and radiation that heat may transfer. Conduction is the movement of heat by direct transfer of molecular energy within solids, for example, heat transfer through metal containers or solid foods. Convection is the transfer of heat by group of molecules that move as a result of differences in density, for example in heated air, or as a result of agitation, for example in agitated water bath. Radiation is the transfer of heat by electromagnetic waves, for example in an electric grill (Hayhurst, 1997).

Canning is an effective means of food preservation. To produce shelf-stable products, sufficient heat processing must be utilized to destroy spoilage and pathogenic microorganisms. Heat processing is only effective if the product is in an hermetically sealed container that maintains its integrity through processing, distribution, and ultimate utilization by the consumer. Potential microorganisms include bacteria, molds, and yeasts. Vegetative cells are those that can most easily be destroyed by heat. Some microorganisms have the ability to produce heat resistant spores. Subsequent outgrowth of the spores leads to the proliferation of vegetative cells that may result in product spoilage and potentially food-borne illnesses. In order to destroy certain spores, the product must be heat processed to at least 115.6°C for extended periods of time. Factors that affect the survival of microorganisms during heat processing include salt, nitrite, pH, moisture and fat content, and level of microbial contamination. The potential danger and impact of botulism is a major concern in the manufacture of shelf-stable products. Therefore, manufacturers must take every precaution to assure that approved procedures are stringently followed. Specific procedures for canned meats, including corned beef hash, beef stew, chili con carne, Vienna sausages, and meat balls with gravy, are well documented by Pearson and Tauber (1984).

Pasteurization is heat processing at a lower temperature (usually below 100°C) than the sterilization process involved in canning. Although there is less damage to the texture, color, flavor, and nutritional content of food, the shelf-life of the product is shorter than those processed for commercial sterilization. Pasteurization can be accomplished by heat processing in water. Water cooking can be used for products packaged in moisture-impermeable containers or films. Water cooking does not produce products that are shelf-stable but require refrigeration.

Boiled ham is a sectioned and formed product that can be packaged in a moisture-impermeable film that is tested to withstand the normal water temperatures of 71.1-79.4°C during the cooking process. The U.S. Department of Agriculture requires approval of such film to ensure that under specified water-cook temperatures the film does not react or deposit undesirable components on the meat. Boiled ham is frequently cooked to an internal temperature of 65.6°C (Claus *et al.*, 1994).

2.1.1. Thermal Kinetics

The destruction or formation of food qualities such as texture, color, vitamins, and aroma compounds by heat follows a similar first-order reaction to microbial destruction. In general, quality parameters are more thermal resistant than microorganisms. As a result, nutritional, sensory properties and qualities are better retained by the use of higher temperatures and shorter times during heat processing. Therefore, it is possible to select particular time-temperature combinations to optimize a process for nutrient retention or preservation of desirable sensory qualities. This concept forms the basis for individual quick blanching, high-temperature short-time (HTST) pasteurization, and ultrahigh-temperature (UHT) sterilization (Fellows, 2000).

2.1.1.1. Kinetics of microbial destruction

Thermal processes are primarily designed to eliminate or reduce the number of microorganisms to an acceptable level (commercial sterility) and provide conditions that limit the growth of pathogenic and spoilage microorganisms. The rate of destruction is a first-order reaction. When food is heated to a temperature that is high enough to destroy contaminating microorganisms, the same percentage die in a given time interval regardless of the numbers present initially. This is known as the *logarithmic order of death* and is described by a *death rate curve* (Fig. 2.1) (Stumbo, 1973).

The time needed to destroy 90% of the microorganisms is referred to as the *decimal reduction time* or D value (Fig 2.1). D values differ for different microbial species, and a higher D value indicates greater heat resistance.

The destruction of microorganisms is temperature dependent; cells die more rapidly at higher temperatures. By plotting D values at different temperatures, a

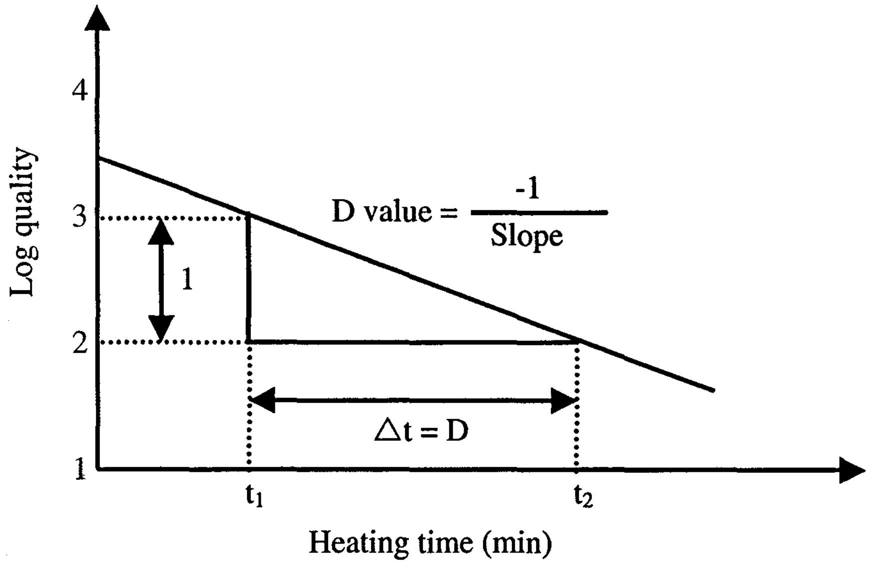


Figure 2.1 Typical D value curve

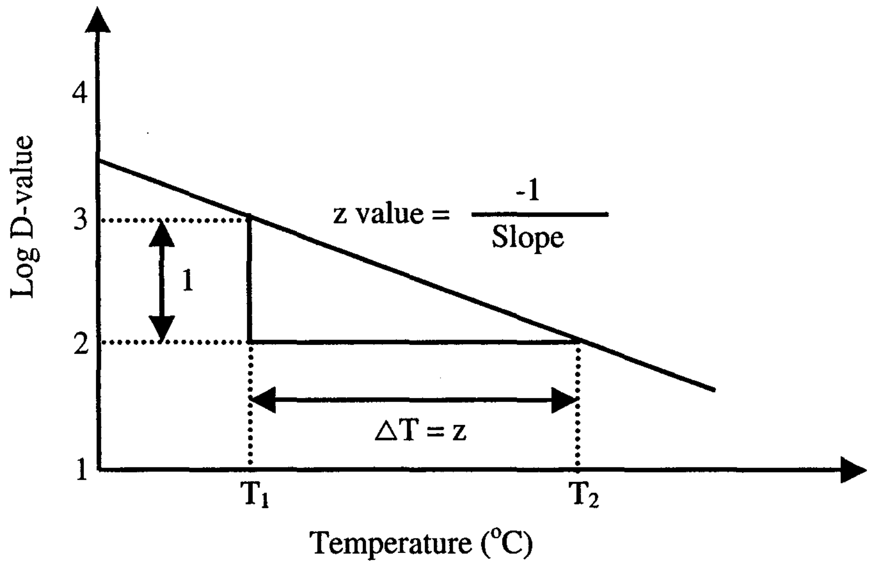


Figure 2.2 Typical z value curve

thermal death time (TDT) curve is constructed (Fig. 2.2). The slope index of the TDT curve is termed the z value and is defined as the number of °C required to bring about a ten-fold change in decimal reduction time. The D and z value are used to characterize the heat resistance of a microorganism and its temperature dependence, respectively.

2.1.1.2. Kinetics of quality degradation

To accomplish the primary objectives of thermal processing (optimize the retention of quality factors while providing a risk-free food) it is necessary to obtain quantitative data on the thermal degradation of microorganisms, enzymes, and quality factors. There have been numerous studies on the degradation kinetics of these components, which have been summarized in several reviews (Lund, 1975 and 1988; Fellows, 1988; Bender, 1978; Tragardh and Paulsson, 1985; Villota and Hawkes, 1986).

In general, the loss of quality has been found to fit zero- or first-order reaction kinetics (Labuza, 1982; Labuza and Riboh, 1983; Ramaswamy and Abdelrahim, 1991):

$$-\left(\frac{dC}{dt}\right) = kC^{n} \qquad [2.1]$$

where C = concentration of the desired quality attribute, t = time, k = reaction rate constant, and n = reaction order. Assuming a first-order reaction rate, the decimal reduction time D can be found to be reciprocally related to k $(D = 2.303/k)$. With the exception of photochemical reactions and some physical reactions, the rate constant of a reaction is strongly dependent on the temperature. The relationship between rate constant and temperature is usually modeled either by the Arrhenius equation:

$$k = k_0 e^{-\frac{E_a}{RT}} \qquad [2.2]$$

where k = reaction rate constant at T, k_0 = frequency factor, E_a = activation energy, R = gas constant, and T = absolute temperature or by the TDT concept:

$$D = D_0 10^{\frac{T_0 - T}{z}} \qquad [2.3]$$

where D = decimal reduction time at T, D_0 = D-value at a reference T (usually 121.1°C), and z = temperature range required to change D by a factor of 10.

Caution must be exercised when applying these concepts to foods because of the heterogeneous nature of foods and the associated phase changes (solid fats changing to liquid phase) as temperature rises (Labuza, 1982). Moreover, this expression is considered to be an oversimplification because it results in unrealistic reaction rates in many cases, especially in the underestimation of protein denaturation.

Assuming N_0 and N are microbial counts, C_0 and C are concentrations of a test nutrient before and after processing, respectively; D_{n0}, D_n, D_{c0}, and D_c are decimal reduction times for the microorganism (subscript n) and quality (subscript c), respectively; and the reference temperature to be T_0 and process temperature to be T, the relative destruction of nutrients with respect to microorganism can be found using the following equation (Ramaswamy and Abdelrahim, 1991):

$$\log\left(\frac{C}{C_0}\right)=\left[\frac{D_{n0}}{D_{c0}}\right]\left[\log\left(\frac{N}{N_0}\right)\right]\left[10^{(T_0-T)\left(\frac{1}{zn}-\frac{1}{zc}\right)}\right] \qquad [2.4]$$

An alternative equation with similar notations, a reaction rate constant k, an activation of energy E_a, and absolute temperature T, using the Arrhenius approach can be written as

$$\log\left(\frac{C}{C_0}\right)=\left[\frac{k_{c0}}{k_{n0}}\right]\left[\log\left(\frac{N}{N_0}\right)\right]\left[e^{\frac{\left(\frac{1}{T_0}-\frac{1}{T}\right)(E_{ac}-E_{an})}{R}}\right] \qquad [2.5]$$

Equations 2.4 and 2.5 can easily be used to calculate, at any given processing temperature, the extent of degradation of any quality relative to that of a microbial population provided the kinetic data for both are known (Ramaswamy and Abdelrahim, 1991).

2.1.2. Effect of Thermal Processing on Food Quality

It is widely recognized that thermal processing, in addition to ensuring a safe food supply, also affects product quality. There are a number of definitions of "quality" of foods, which are discussed by Cardello (1998). In general, quality has been defined as "the composite of those characteristics that differentiate individual units of a product, and have significance in determining the degree of acceptability by the buyer" (Kramer and Twigg, 1970). These characteristics include those which are external (color and texture), internal (flavor, mouthfeel or consistency perceived by the senses of taste and small) and other less tangible characteristics which are more difficult for consumers to assess (nutritional properties and microbiological quality) but are nevertheless important in determining acceptability and purchase of a product (IFT, 1990). In order to improve the overall quality of a food, a thorough understanding of the chemical basis of quality factors is necessary (Abbatemarco, 1993).

2.1.2.1. Color

The color of a food product is a primary indicator of quality and the principal basis for acceptance by consumers. The appearance of a food is the most important quality factor; it undoubtedly affects consumer perception of other quality characteristics such as flavor and texture. Hutchings (1977) described its major role in the total human perception of food. Due to problems with subjectivity and an overall lack of reproducibility, instrumental color measurements for quality grading are most often carried out in the food industry (Hunter, 1975) for which there are several instruments and color evaluation techniques commercially available.

The study of food color is conducted for several reasons: to maintain a uniformity of color over production runs (Pearson, 1996), to avoid the color changes brought about by chemical reactions occurring during processing or storage life of the product (Bard & Townsend, 1978), to optimize the color and appearance in relation to consumer preference, and to maintain the color in accordance with consumer experience and expectations (Rust, 1976).

Tristimulus colorimeters are widely used to objectively describe color as a combination of the three primary color intensities (red, green and blue) as a specific point in a three dimensional space. One of the most popular systems makes use of Hunter L, a, b notation (Francis and Clydesdale, 1975) for describing instrumental sensitivity to color. "L" is a lightness/brightness indicator (a higher L value indicates a lighter/brighter sample), "a" estimates the degree of greenness (if negative) or redness (if positive) and "b" estimates blueness (if negative) and yellowness (if positive) (Abbatemarco, 1993).

Methods to assess the color and appearance of foods are described by MacDougall (1984). Many naturally occurring pigments are destroyed by heat processing or chemically altered by changes in pH or oxidized during storage. As a result, the processed food may lose its characteristic color and hence its value but color in most processed foods are more stable to heat, light and changes in pH.

2.1.2.2. Texture

Texture is a valuable external quality characteristic of foods and is quite variable depending on the type of food, its composition and whether it is fresh or processed. Texture of product may be defined as "the sensory manifestation of the structure of the food and the manner in which this structure reacts to the applied forces, the specific senses involved being vision, kinesthetics and hearing" (Szczesniak, 1991). The texture of foods is commonly dictated by the moisture and fat contents and the types and amounts of structural carbohydrates (such as cellulose, starches and pectic materials, and proteins that are present). Changes in texture are caused by loss of moisture or fat, formation or breakdown of emulsions and gels, hydrolysis of polymeric carbohydrates, and coagulation or hydrolysis of proteins. Detailed information on the textural characteristics of food is given by Mohsenin (1980), Lewis (1990) and Szczesniak (1983). The effect of food composition and structure on texture is described by Stanley and Tung (1976) and Sherman (1976).

Based on fundamental rheological principles, textural characteristics have been defined and classified into mechanical and geometrical qualities as well as those related to the moisture and fat content of a product. The mechanical characteristics were subdivided (Szczesniak, 1963) into the 5-primary parameters of hardness, cohesiveness, viscosity, elasticity, and adhesiveness, and into the 3-secondary parameters of brittleness, chewiness, and gumminess. These properties referred to the manner in which the food was perceived in the mouth and were defined as follows, for a given sample:

2.1.2.2.1. Primary parameters

Hardness: the force necessary to attain a given deformation.

Cohesiveness: the strength of the internal bonds making up the body of the product.

Viscosity: the rate of flow per unit force.

Elasticity: the rate at which a deformed material goes back to its undeformed condition after the deforming force is removed.

Adhesiveness: the work necessary to overcome the attractive forces between the surface of the food and the other surface of content (e.g., tongue, teeth, palate, etc.)

2.1.2.2.2. Secondary parameters

Brittleness: the force with which the material fractures and is related to the primary parameters of hardness and cohesiveness.

Chewiness: the energy required to masticate a solid food product to a state ready for swallowing and is related to the primary parameters of hardness, cohesiveness, and elasticity.

Gumminess: the force required to disintegrate a semisolid food to a state ready for swallowing and is related to hardness and cohesiveness.

The most popular devices used for the measurement of texture include the Kramer Shear Press, the Instron Universal Testing Machine, Ottawa Texture Measuring System, General Foods Texture Meter and Texture Analyser which are used for many different types of food products.

2.1.3. Limitations of Thermal Processing

The application of conventional heating equipment usually has an adverse effect on the taste of the treated food product. The deficiencies of conventional heat technologies stem from the heat transfer mechanism, which is based on transfer of heat from a hot wall as in the case of in-container heating or tube wall to the product such as tubular heat exchanger in continuous flow heating. In order to reach the desired temperature throughout the product, the temperature of the wall must be significantly higher than the temperature of the product being heated. Even though an adequate conventional processing is able to inactive the pathogenic and spoilage microorganisms, it also increases the risk of fouling and scorching the product near the walls which leads to the formation of off-flavors and/or causes excessive degradation of the product quality. In addition, it is an energy intensive and slow heating process.

While several innovative alternatives such as rotational, thin profile and aseptic processing have evolved to reduce some of the above shortcomings, other innovative heating techniques such as microwave heating, radio-frequency heating and ohmic heating have provided additional alternatives. Ohmic heating, which is the principal focus of this study is detailed in the next section.

2.2. OHMIC HEATING

Also termed "resistance heating" or "electro-heating", this is a more recent development in which an alternating electric current is passed through a food, and the electrical resistance of the food causes the power to be translated directly into heat. As the food is an essential component of the heater, it is essential that its electrical properties (its resistance) are matched to the capacity of the heater.

2.2.1. Historical Perspectives

A number of attempts have been made to use this technique in several food processing applications over the past century (de Alwis and Fryer, 1990; Palaniappan and Sastry, 1990) starting from the first application in liquids (Jones, 1897). During the 1950's and 70's, experiments involving ohmic heating was used for thawing purposes foods (Naveh *et al.*, 1983). Thawing rates were faster, but satisfactory results relied upon good contact between the food and the electrodes.

Difficulties arose with complex geometry. More recently, a patent (USA) was obtained by Ohtsuki (1990) for thawing frozen foods using a three-electrode system with voltages ranging between 0.5 and 20 kV and a current density range of 0.02-0.3 A/m. The thawing of frozen blocks of fish by immersion in warm water was done by a traditional method. The major disadvantage of using this method is the requirement of large amounts of fresh water resulting in wastewater. The surface microbial quality of foods is compromised due to the water temperature of 30°C. Also, valuable soluble proteins are leached. More recently, microwaves have replaced this technology for thawing. Ohmic heating have been used on peeled and cut potato slices and corn on cob in order to inactivate enzymes. An industrial process named "OSCO" was developed in the 1970's to treat peeled and cut potatoes in solution prior to frying. Ohmic heating has been utilized as a rapid heating method for frankfurters, by placing of electrodes at both ends of the sausages. Rapid heating methods for vending applications were developed to heat sausages, pizzas and hamburgers between 1930-1970. Microwaves are presently used as a more convenient alternative. The introduction of reliable aseptic packaging technology followed early concepts in the use of ohmic heating for pasteurization and sterilization. In order to sterilize foods by ohmic heating, cans were designed to include electrodes fixed either permanently or temporarily on containers. In the late 1920's, continuous ohmic pasteurization was introduced in the USA for the pasteurization of milk which included the "Electro-Pure" process (Anderson and Finkelstein, 1919). Fifty industrial electrical milk sterilizers were in operation in the 1930's (Getchell, 1935; Moses, 1938) but disappeared in the

1950's. de Alwis and Fryer (1990) presented a review of problems in the early development of the ohmic heating technique, the major one resulting from improper contact between electrodes and the food product. Following the use of unsuitable electrode materials, electrolysis and product contamination were observed. Adhesion of the product to the electrodes often occurred. The reason for poor experimental results were due o the difficulty of ensuring good contact between electrodes for complex solid geometry.

The development of the "ELECSTER" process for the pasteurization of milk based on the "Electro-Pure" process and the "APV Baker Ohmic Heating Technology" for the sterilization of particulate foods (Skudder, 1991) are the most recent industrial achievements in ohmic heating. The latter technology was recognized as a commercial breakthrough at the 1996 Annual Meeting of the Institute of Food Technologists (IFT). For the development of the ohmic heating technology for the sterilization of fluid containing particles, APV Baker Ltd. received the IFT Industrial Achievement Award (Giese, 1996). In order to help European food companies in developing sterilization processes for liquids containing particles, in 1995, the CTCPA (Centre Technique de la Conservation des Produits Agricoles, France) and UTC (Universite Technologique de Compiegne, France) joined forces to install an APV pilot plant unit.

Renewed interest has been observed for developing heating (i.e., blanching, sterilizing and cooking), thawing or gel forming technologies using ohmic heating principle. In some cases, it may be as economical as other conventional processes (Allen *et al.*, 1996). A considerable amount of attention has been given to ohmic heating for its thermal processing of foods due to rapid and uniform treatment along with its high-energy efficiency and technical simplicity. The evaluation of the design and the performance of an ohmic heating unit for the thermal processing of liquid foods was done by Qihua *et al.* (1993). In a newly designed continuous unit, it was determined that the outlet temperature and the rapid establishment of a steady state was mostly controlled by the voltage gradient and low rate for given electrical conductivities and other properties of the fluid and inlet temperature.

Mizhrahi (1996) found that ohmic heating can provide an effective method for blanching large vegetables since the process can be accomplished in a relatively short time regardless of the shape and size of the product. As a result, the need for dicing as commonly performed prior to water blanching could be eliminated. For a vegetable of similar size, the extent of solute leaching during 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. As a consequence, ohmic heating used for large pieces of vegetable could efficiently reduce the extent of solute leaching. An alliance in France was formed to design, build and evaluate a pumpable ohmic heating unit for processed meats (Peyron, 1996). The alliance involved the ADIV (Association pour le developpement de l'industrie de la viande, France) and EDF (Electricite de France, France). They found that there was not a significant difference between conventional and ohmic heating on the yield, microbiology and sensory evaluation of two products (i.e. pate de foie et pate de campagne). The ohmic heating time, however, was 10-20 times less than the conventional cooking operation.

Early investigations of ohmic heating (Jason and Sanders, 1962ab; Sanders, 1963; Burgess *et al.*, 1967) revealed that hot spots appeared since enough heat is generated to cook. Henderson (1993) showed that hot spots occur simultaneously on localized regions and could be controlled by the supply of electrical current. Huang *et al.* (1997) used a batch type ohmic heater to coagulate fish proteins from the frozen fish mince. Yongsawatdigul *et al.* (1995a) found that ohmic heating maximized the gel functionality in Pacific whiting surimi as compared to the conventional heat treatment. A fully automated prototype for ohmic thawing of fish blocks based on the control of current flow within the product to eliminate the formation of hot spots was successfully designed by Roberts *et al.* (1998).

A novel continuous ohmic heating process for liquids was evaluated by Uemura *et al.* (1996b). A 2 cm diameter tube was used. Ring electrodes were inserted into the wall of the tube and then spaced. A constant voltage was applied (20 kHz and 68 V) to the two electrodes. The most significant factor influencing the temperature profile was the space between the electrodes. This system represents another option which could be used as an alternative to the APV system for fluids. Recently, a research group (Société TECNAL, France) applied ohmic heating to a large diameter tube which permit to transfer a highly viscous product, such as meat emulsion (Causse, 2001).

Another possible application of ohmic heating is the concentration of fluids. In highly viscous products, where fouling might occur, this technique is advantageous. In France, EDF (Electricite de France) and CTP (Centre Technique du Papier) have worked together on the design of a continuous ohmic heating concentrator for the pulp and paper industry (Aussudre, 1996). In order for it to be efficient, electrical conductivity values should range between 0.01 to 10 S/m. The concentration of species in the solution influenced electrical conductivities. As the concentration increased, electrical conductivity increased until the concentration reached a certain level after which the electrical conductivities diminished. When designing a concentration unit, it is crucial to take into account that the electrical conductivity will change with the concentration and temperature. The ohmic heating principle was used as a rapid heating method to design a laboratory apparatus for fat analysis in meat products (Piette and Jacques, 1997a).

2.2.2. Mechanism of Ohmic Heating

Food which contain water and ionic salts are capable of conducting electricity, but they also have a resistance which generates heat when an electric current is passed through them (Skudder and Biss, 1987). The generation of heat occurs volumetrically. The temperature rises when electrical energy is directly converted into heat. An electrical circuit consists of a resistance, a source of current and an applied voltage. When the food product is placed between two electrodes and the current passes through it, the food product acts as the resistance. Therefore the food becomes part of an electrical circuit. To describe this principle of heating, other synonyms are used such as: direct resistance heating, Joule effect heating, electro-conductive heating and electro-resistance heating. Convection or conduction heat transfer mechanisms are minimal. This method offers an alternative to heat food rapidly which bypasses the conventional heating system. Pain *et al.* (1995) categorized available direct volumetric heating techniques: steam (e.g. injection and infusion), radiation (e.g. infrared, microwave and radio frequency) and the Joule effect which is the ohmic heating.

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

$$Q = E^2\sigma \text{ or } (\nabla V)^2\sigma \qquad [2.6]$$

Where ∇V or E is the voltage gradient (V/m) or electric field density and σ is the local electrical conductivity.

Most commercial ohmic heaters function under constant voltage conditions. In the absence of other significant heat transfer mechanisms such as convection and/or conduction, and neglecting heat losses to the surroundings the heating rate under constant voltage conditions may be calculated from:

$$\frac{dT}{dt} = \frac{\sigma(\nabla V)^2}{(\rho C_p)} \qquad [2.7]$$

It is common that high heating rates in the range of 1-10°C/s are observed. A commercial residence time of 10-100 s is possible to obtain a temperature rise of 100°C in the food (Stirling, 1987). The rise in temperature in each section of an APV continuous ohmic heater tube (Skudder and Biss, 1987) may be calculated from Equation [2.8]:

$$\Delta T = \frac{V^2\sigma A}{(LmC_p)} \qquad [2.8]$$

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

$$P = mC_p\left(T_{out} - T_{in}\right) \qquad [2.9]$$

It is suggested (Skudder and Biss, 1987; Marcotte, 1999) 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 2.10-2.13):

$$P = VI \qquad [2.10]$$

$$P = RI^2 \qquad [2.11]$$

$$P = \frac{V^2}{R} \qquad [2.12]$$

$$V = RI \qquad [2.13]$$

The ohmic heating system may be limited voltage and current may be applied. Voltages of 12 kV are readily available. In a commercial setting, a 3.3 kV per phase is commonly used and easily controlled.

2.2.3. Advantages of Ohmic Heating

As highlighted in Biss *et al.* (1989) and Marcotte (1999), Ohmic heating offers numerous benefits. The most important one is the rapid heating which occurs within seconds. The food is heated rapidly (1-10°Cs^{-1}) at about the same rate throughout and the absence of temperature gradients results in uniform heating of solids and liquids if their resistances are matched. The heat transfer coefficients do not limit the rate of heating. Therefore, temperatures necessary for UHT processing can be achieved. Since there are no hot surfaces for heat transfer as in conventional heating, the risk of surface fouling or burning of the product is reduced which results in less frequent cleaning. Consequently, heat sensitive foods or food components will not be damaged by localized over-heating.

This process is also good for heating shear-sensitive products. Particles are handled more gently and are able to maintain their integrity when using an ohmic heater as compared to a scraped surface heat exchanger (SSHE). The processed food retains excellent qualities such as flavor, color and texture and even has a longer shelf life in some food products. The ohmic heating is energy efficient and includes particles in suspension. It is suitable for viscous liquids because heating is uniform and does not have the problems associated with poor convection for these materials. The ohmic heating system can reduce particle damage, is silent in operation and facilitate easy maintenance as there are no moving parts with the heater. It is an environmentally friendly system.

Ohmic heating is more efficient and lower in capital cost than microwave heating because nearly all of the energy enters the food as heat. Due to this, energy conversion efficiencies are very high (90%). Another important difference is that microwave and radio frequency heating have a more limited depth of penetration than ohmic heating. However, microwave heating does not require contact with the food, whereas ohmic heating requires that electrodes to be in good contact. During the operation, a high level of control and automation ensures safety. Futher details are given by Sastry (1994), Rahman (1999), Fellows (2000), Marcotte *et al.* (1998).

2.2.4. Effects of ohmic heating on foods

In general, ohmic heating is considered as a thermal process i.e. heat energy is generated within the electrically resistant food system when an electrical current passes through it. Electrical treatment of foods can be used in various ways (Palaniappan and Sastry, 1990) which may cause additional electrical or non-thermal effects on food systems. Meanwhile, either alternating (AC) or continuous current (DC) may be applied. Electrical treatment may be delivered by continuous or rapid discharge (pulses) with or without any heat generation. For ohmic heating, the voltage range is between 3 kV and 12 kV while the high voltage impulses range is between 14 kV and 35 kV. The investigation of low frequency technologies have made possible the "cold" pasteurization with electrical fields (Jayaram and Castle, 1992; Castro *et al.*, 1993) and oscillating magnetic fields (Pothakamury *et al.*, 1993; Barbosa-Canoves *et al.*, 1998).

Under ohmic heating with low frequency (kHz region) conditions, ionic losses and penetration depths are enlarged. Ohmic heating involves the dissipation of electrical energy by conduction into the food product as a dielectric material in contrast to radioactive energy transfer at high frequencies. One issue to consider is that polarization effects that occur result in the out-gassing 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 (Marcotte, 1999).

As summarized by Marcotte (1999), several studies have been conducted to measure the effect of electricity on microorganisms and enzymes in cell suspensions or in food directly under various conditions (Palaniappan and Sastry, 1990; Palaniappan *et al.*, 1992; Imai *et al.*, 1995). Two studies (Palaniappan and Sastry, 1990; Bhat and Joshi, 1998) showed microbial death caused by electricity to be due to 3 effects: mechanical, chemical, and thermal. Furthermore, Palaniappan and Sastry (1990) stated that microbial inactivation during continuous low-voltage alternating electrical treatments has been attributed primarily to heating.

Before the Electro-Pure process (Andersen and Finkelstein, 1919) was approved and commercialized in the early 1920's, it was examined by several US state health departments and determined that there was no adverse electrical effect on milk. Milk was stabilized solely by a thermal effect. It was also noted that, enzymes were inhibited due to the heat generation when a low voltage alternating current was applied (Mizhrahi *et al.*, 1975). A comparison of ohmic to conventional heating was done on suspensions of yeast (*Saccharomyces bailli*) and bacteria (*Escherichia coli*) by Palaniappan *et al.* (1992). They deduced that microbial death was mostly coming from thermal effects with no significant effect due to electrical currents.

Mertens and Knorr (1992), and Barbosa-Canovas *et al.* (1998) found a lethal effect on the microbes when an electrical current involving the use of high-voltage pulses in aqueous suspensions is applied. It is believed that mechanical damage occurs under high voltage impulses. Bacterial death was due to the pores produced in their cell membranes.

Under electro-hydraulic shock conditions, a rapid electrical discharge is applied to a suspension of micro-organisms without any heat generation. Under these situations, the reduction in the number of microorganisms was attributed to oxidation reations (Marcotte (1999).

A comparison between conventional and ohmic fermentation of *Lactobacillus acidophilus* at three temperatures (30, 35 and 40°C) was studied by Cho *et al.* (1996). By using the process of ohmic heating, a steady temperature was retained by intermittently circulating cooling water through the water circulation coil. It was discovered that the electric current enhanced early stages but slightly inhibited the late stages of growth. Bacteriocin production was decreased during the ohmic heating process. It was also possible to monitor the progress of the fermentation by monitoring the current at a constant voltage. Schade (1951) and Mizhrahi (1975) found that ohmic heating could be successfully applied to blanching on potato and corn. They reported that the ohmic treatment inhibited enzymes responsible for discoloration such as enzymatic browning.

2.2.5. A Typical Ohmic Heating Setup

The design of ohmic heating system must include the electrical properties of the specific product to be heated, because the product itself is an electrical component. This concept is only found elsewhere in radio frequency heating and requires more specific design considerations than those needed when choosing other types of heat exchangers. Ohmic heating system should therefore be tailored to a specific application and the factors taken into account such as the type of product (electrical resistance and change in resistance over the expected temperature rise), the flow rate, the temperature, the heating rate, and the holding time (Fellows, 2000).

Early designs used DC power, which caused electrolysis (corrosion of electrodes and product contamination) and also had expensive electrodes. The use of AC power supply at 50 Hz reduces the risk of electrolysis and minimizes the complexity and cost. Alternatively, higher frequencies (>100 kHz) or carbon electrodes may be used to reduce electrolysis.

A commercial ohmic heater setup can be seen in the context of a complete product sterilization or cooking process where there is already a holding tube, pumping and a cooking system. A typical aseptic processing line with an ohmic heater is shown in Figure 2.3 (Marcotte, 1999). In this case, the ohmic heating column consists of 4 electrodes. The food product is introduced vertically from the bottom 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, if necessary. It is then cooled in tubular heat exchangers before being packed in an aseptic environment. Commercial APV ohmic heating installations are available for different production throughput.

2.2.6. Validation Aspects of Ohmic Processing

Based on the safety aspect, the worst case circumstance of thermal process calculation should also be concerned for ohmic heating (Larkin and Spinak, 1996). The situation with respect to ohmic heating is less familiar than traditional sterilization processes and therefore may require new constraints. Certain

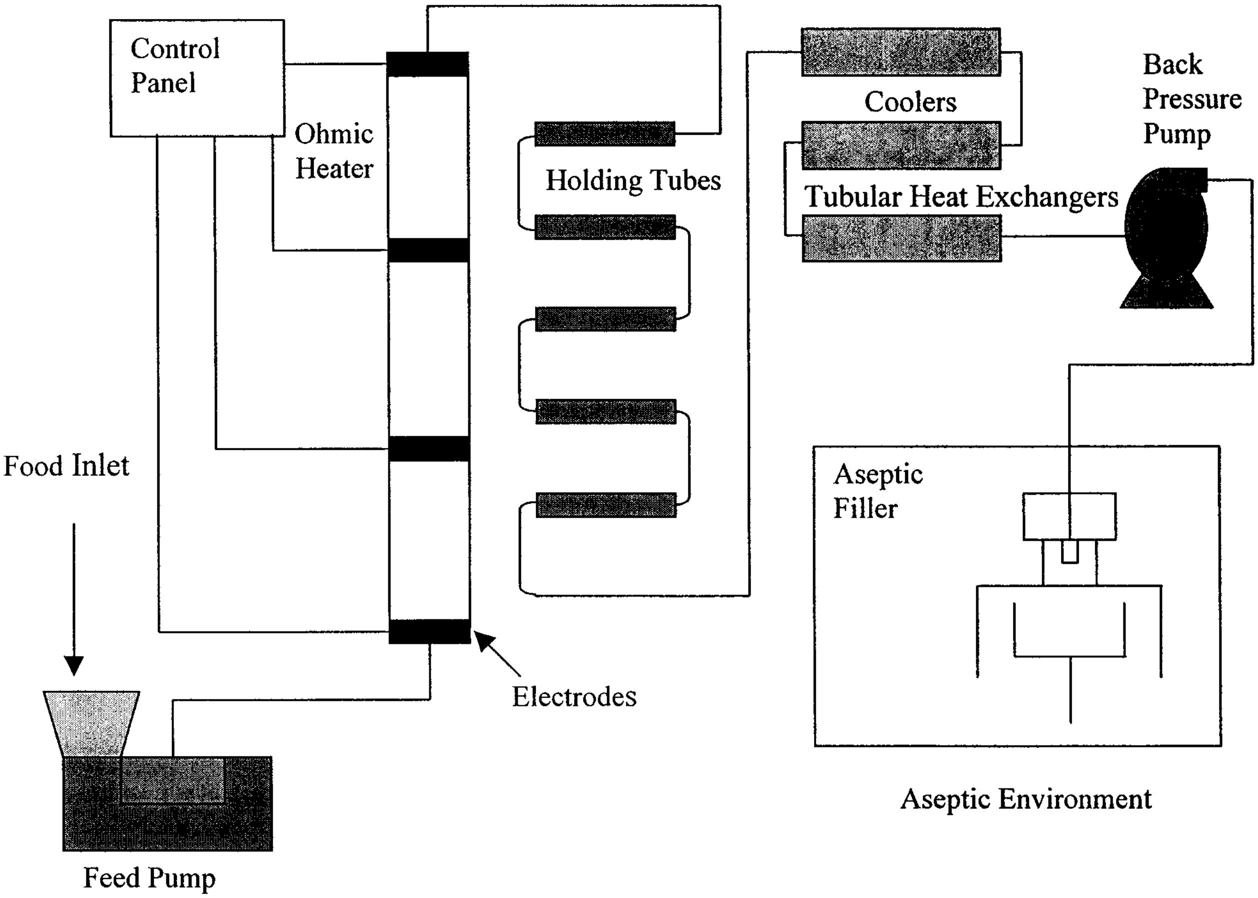


Fig 2.3 An aseptic processing line with an ohmic heater

Adapted from Marcotte (1999)

important issues to be considered during the establishment of an ohmic heating process are summarized by Sastry (1991). There should be a close match between electrical conductivities of solid and liquid phases and their temperature coefficients. Particle concentration may play a critical role if the electrical conductivity in solid phase is lower than the liquid phase. Higher concentration of particles may result in slower overall heating but quicker heating of the solids. Within the mixture of highest electrical conductivity liquid, the lowest conductivity particle should be identified as the critical particle. It must be noted that particle orientation is extremely important if the particle aspect ratio is far from unity. Slow heating can result in a particle which is oriented parallel to the electrical field permitting a maximum current by-pass and having a minimal cross-sectional surface area exposed to the current. These effects are relatively small when dealing with cubic and spherical particles. The size of the particle has a minor effect on heating rates.

Fryer and de Alwis (1989) suggested a procedure by which an ohmic process can be confirmed in terms of safety and 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 sterilize the worst case in the worst orientation; 3) Carry out tests to determine the effect of the process on the fastest heating component to verify for unwanted degradation; and, lastly, 4) Perform additional tests on any component known to be thermally labile.

2.2.7. Commercial Ohmic Heating Installations

APV ohmic heating installations are available for various production capacities in commercial continuous/aseptic processing. For example, a 30, 75, 125, 300 and 600 kW units used for 300, 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 used for pilot scale units is 10 kW for continuous production of 100 kg/h. The development of ohmic heating technology for particulate foods was first formulated by the Electrical Research Council in Capenhurst, England. For commercial exploitation of the results, it was licensed to APV Beker Ltd. APV patented the electrode assembly in England (Simpson, 1980) and the United States (Simpson, 1983). Europe, Japan and the United States experienced the installations of over 18 commercial industrial plants. The following authors have reported on the commercial applications of the APV ohmic heating technology for particulate foods: Taffe (1987); Frampton (1988); Swientek (1988); Grikitis (1989); Sperber (1992); Anon (1994); Rice (1995); Tjomb (1995); Pain *et al.* (1995) and Anon (1996). Some examples of commercial ohmic heating units used for laboratory, pilot and industrial applications with food systems are summarized in Table 2.1 (Marcotte, 1999).

2.2.8. Ohmic Heating & Electrical conductivity

Electrical conductivity plays an essential role in ohmic heating. The ohmic heating rate is controlled by the electrical conductivity or the overall resistance of

Table 2.1 Applications of commercial ohmic heating units for laboratories, pilot plants or industries (Marcotte, 1999).

Organization	Year	Country	Power (kW)	Food Product
Electricité de France	2000	France	NA	Commutated meat sausage
Lasssoudry	2000	France	70	Surimi
Alfa-Laval Vicarfb	1999	France	44	Egg, milk, juice and fruit puree
Raztek	1997	US	10	Liquid and viscous food products
Emmepiemme (Ouest Process Alimentaire)	1990's	France	50 & 100	Fruit and tomato sauce
EPRI	1996	US	NA	NA
CTCPA	1995	France	10	Pilot scale installation
NCFST/FDA/APV	1994	US	5	Dynamic batch Ohmic heating unit for research tests
AFS (Advanced Food Science) Land O'Lakes	1992	US	5	R & D assistance for product development, a continuous system
UTC	1990	France	5	Capacity of 1 kg perbatch at a laboratory scale
Sous Chef Ltd (H.J. Heinz division)	1989	UK	75	Prepared meals of meat and vegetables
Nissei Co. Wildfruit Division (1 of 6 ohmic heaters)	NA	Japan	75	High acid particulate foods such as whole strawberries in syrup
Chef Mate Brand (Nestlé Food Service Division)	NA	US	300	Shelf stable low acid beef stew and ravioli in can packaging
Odin Packaging Systems	NA	Italy	NA	Testing facilities for a full range of products
Confidential	NA	Europe	75	High acid products such as fruits in syrup and vegetables and meats
Confidential	NA	Europe	300	Low acid particulate foods
Confidential	NA	Japan	300	High acid particulate foods
Confidential	NA	Japan	75	Prepared meals

food. However, the optimal level of conductivity or resistivity within the food sample to fulfill a desirable temperature rise varies (Marcotte, 1999). Within highly conductive materials, such as metals, a high current will flow. There will be a negligible current in insulators or highly resistive materials such as wood. It is crucial to note that in both these conditions, generation generation of heat will not be sufficient. Consequently, boundaries exist for the values of electrical conductivity in order to obtain sufficient heat generation. If food electrical conductivity fall outside this region, it would represent a potential threat to the process. In excess of 30% and dissolved ionic species such as salts and acids which render the food electrically conductive in order to benefit from ohmic heating (Halden *et al.*, 1990). Materials which are not suitable for ohmic heating are pure fats, oils, alcohols and sugars. These substances are electrically too resistive. Highly conductive materials (e.g. very concentrated salt solutions) which would allow most of the current to pass through would not be appropriate. There is a particular operating region of electrical conductivities (Figure 2.4) which would provide a successful ohmic heating process, within a maximum and physically limited power (de Alwis and Fryer, 1992). On the other hand, there is sufficient flexibility to adjust food formulations by mixing highly conductive and resistive food ingredients so that the overall conductivity is optimal for the possible efficiency of the ohmic heating process (Zoltai and Swearingen, 1996). In a heterogeneous mixture, there is a higher rate of increase in electrical conductivity of potato particle as a function of temperature than for a carrier fluid of various electrical conductivities as demonstrated by Sastry (1992).

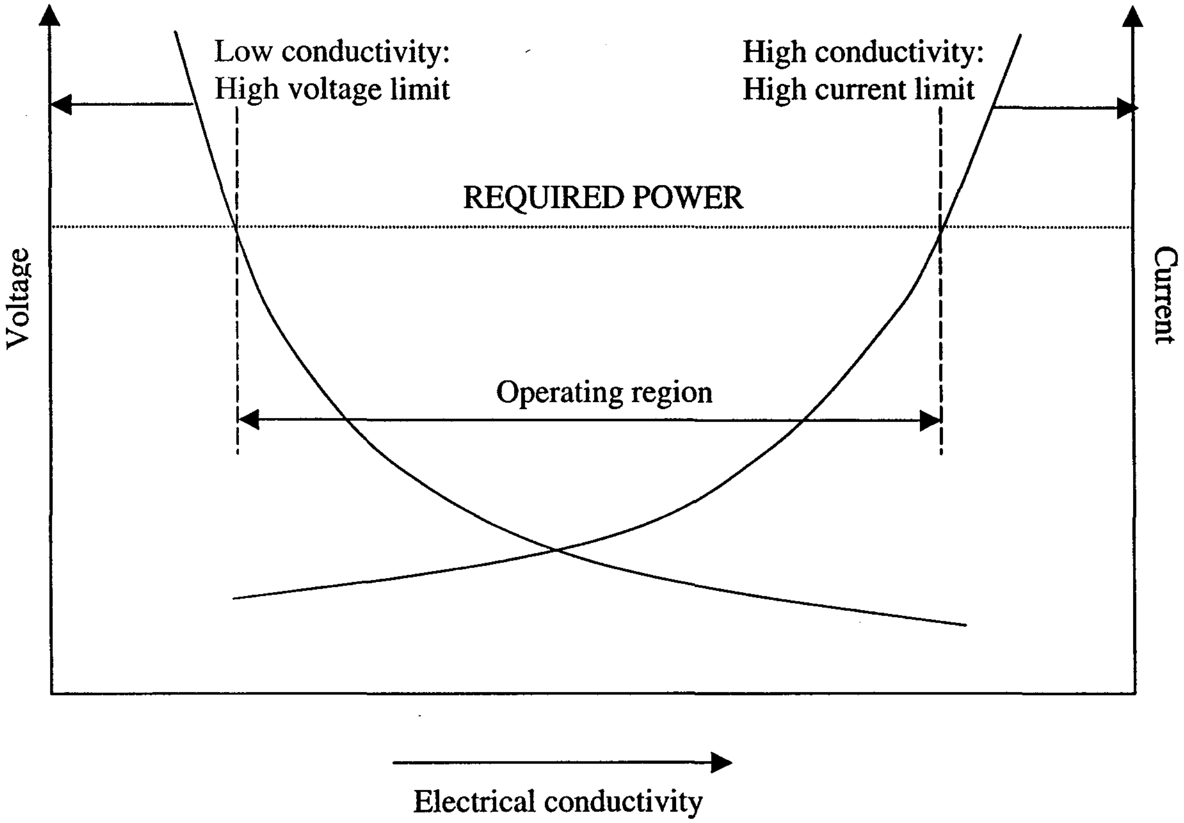


Figure 2.4 Operating region of electrical conductivity

Adapted from de Alwis and Fryer (1992)

2.2.8.1. Measurement of electrical conductivity

In order to measure electrical conductivities of solid food pieces various geometry devices have been developed (Mizhrahi *et al.*, 1975; Mitchell and de Alwis, 1989; Palaniappan and Sastry, 1991a) as it was difficult to find commercial meters that would give satisfactory results at the frequency generally encountered during ohmic heating. In its simplest form, the 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 between 1 to 50 cm^{-1} (Cumming and Torrance, 1985; Marcotte, 1999). Frequently, the current is measured when a fixed voltage is applied. The precise geometry of the sample must be known. A ratio of the distance to diameter of four was found to render 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 equal or higher than 1kHz (Mitchell and de Alwis, 1989; Halden *et al.*, 1990). 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 electrodes to area of electrodes). It is common practice to maintain the resistance between limits of 10 and 100000 ohms. The majority of food liquids would require a practical cell constant of 50 cm^{-1} (Jones, 1985). In order to accurately measure the conductivity, it is necessary to determine the cell constant. While it is possible to measure the geometry of the cell, it is common practice to measure the resistance when the cell is filled with a solution whose electrical conductivity is accurately known. For the purpose of reference, 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 a large distance between electrodes). When dealing with small conductivities, the ratio L/A should be very small. Therefore, large electrodes will be applied and the length between electrodes will be short. It has been reported that there is no voltage gradient effect on electrical conductivities of liquids (Crow, 1979; de Alwis *et al.*, 1989, Palaniappan and Sastry, 1991b; and Yongswawatdigul *et al.*, 1995b). 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). When using commercial applications the choice of frequency is usually a compromise between avoiding polarization problems without introducing capacitive errors into the measurements (Mitchell and de Alwis, 1989; Kim *et al.*, 1996a; Fryer *et al.*, 1993). Since the effect of the frequency 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. The electrical properties of foods at low frequencies in the context of ohmic heating has received little attention (Mitchell and de Alwis, 1989).

2.2.8.2. Electrical conductivity of solids

Most foods in liquid form have higher electrical conductivities than solid particles. 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, soaking treatments have been proposed by Sastry and Palaniappan (1992) and Wang and Sastry (1993).

Several authors have investigated the effect of processing on the electrical conductivity of solid food pieces (Halden *et al.*, 1990; Wang and Sastry, 1997a). As in most industrial operations, product will most probably undergo a thermal treatment for the purpose of cooking, enzyme inactivation or raising the initial temperature prior to ohmic heating. It is important to study the influence of these processes on the associated electrical conductivity since the latter is a key factor in the estimation of the heating rate. During ohmic heating treatment with potato, carrot and yam, it was shown that the electrical conductivities increased at the same rate as their come-up heating rates (Wang and Sastry, 1997a).

Palaniappan and Sastry (1991a) studied the electrical conductivities of untreated potato, carrot and yam samples soaked in various salt solutions (from 0 to 0.8%) until equilibrium saturation. It was observed that all vegetable samples that were soaked in water had lower electrical conductivities than the control. The infusion of salt caused an increment in electrical conductivities to the extent of increase dependency on salt concentration.

2.2.8.3. Electrical conductivity of liquids

Palaniappan and Sastry (1991b) reported that the liquid electrical conductivity decreased with the increasing presence of solids or non-polar constituents dispersed in the liquid phase. The temperature effect was more important than the effect of the percentage of solids, but, still was significant nonetheless. The electrical conductivity of liquids was reported to be usually higher than the electrical conductivity of solids, therefore, this is to be expected.

A common equation was established (Palaniappan and Sastry, 1991b) for the effect of temperature and solids content on the electrical conductivity of tomato and orange juices:

$$\sigma_T = \sigma_{ref}\left[1 + K_T\left(T - T_{ref}\right)\right] - K_S S \qquad [2.14]$$

where S is the solid content, K_T & K_S are constants. It was also revealed that the electrical conductivity was affected by the size of suspended particles. Results of investigations (Palaniappan and Sastry, 1991b) regarding the role of particle size in carrot juice revealed that electrical conduction decreased as the particle size increased. It was proposed that the structural property is more effective than the chemical property on the processed particle size of the sample (Marcotte, 1999).

2.2.8.4. Electrical conductivity of solid/liquid mixtures

On one hand, ohmic heating process is simplified when homogeneous foods such as liquids are used in the processing. On the other hand, when ohmic heating is applied to heterogeneous foods such as a mixture of liquid and solid particles, in general, the conductivity of the system maintains the basic operating conditions. In an ideal situation, the electrical conductivities of solid particles and carrier liquid should have a similar heating rate but this condition is not easy to control. Overall, it is observed that ohmic heating is more efficient if the ratio of solid particles to liquid is high (Marcotte, 1999). Lastly, orientation of irregularly shaped particles in the field was observed to strongly influence the heating rate of the particle in the liquid. The importance of being aware of the effective conductivity of two phase continuous flow systems was pointed out by Palaniappan and Sastry (1991c). However, it is complicated to measure the electrical conductivity of two phase continuous flow systems under all possible conditions.

2.2.8.5. Effect of temperature

Electrical conductivity values are commonly measured at room temperature which is not the temperature at which the food is processed during ohmic heating. Wang and Sastry (1997a) reported that electrical conductivity was significantly influenced by temperature. Electrical conductivity values of pieces of raw vegetable follow a sigmoid curve as a function of temperature with a slope change of around 50°C due to critical structural changes in the biological material (Figure 2.5a). In the case of liquids, formulated products and thermally treated solid vegetable pieces, several authors (Palaniappan and Sastry, 1991ab; Fryer *et al.*, 1993; Qihua *et al.*, 1993; Yongsawatdigul *et al.*, 1995b) have demonstrated that the electrical conductivity increases linearly with temperature between 20 to 80°C (Figure 2.5b). The following equation for viscous liquids was used by Fryer *et al.* (1993):

$$\sigma_T = \sigma_0 + K_T(T) \qquad [2.15]$$

This anchors the reference value of the electrical conductivity at 0°C. The relationship between electrical conductivity and temperature for liquids was

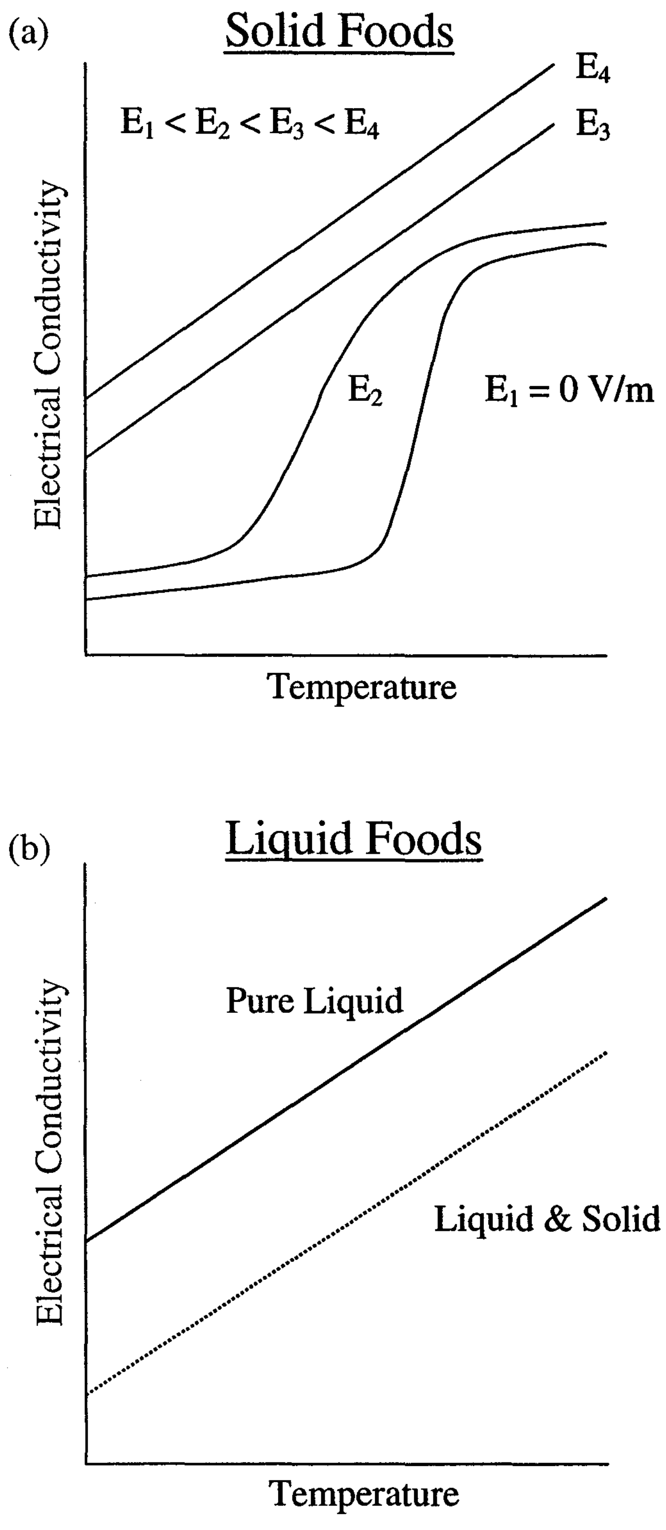


Figure 2.5 Electrical conductivities of (a) solid foods and (b) solids content liquid foods
Adapted from Sastry and Palaniappan (1992); Marcotte (1999)

expressed by Palaniappan and Sastry (1991b) in a slightly different manner:

$$\sigma = \sigma_{25}\left[1 + K_T(T - 25)\right] \qquad [2.16]$$

Roberts *et al.* (1998) reported that electrical conductivity of frozen fish blocks were dependent on temperature and phase. Luzuriaga *et al.* (1996) discovered that thawed shrimps had higher electrical conductivity that was two orders of magnitude different from frozen shrimps. They also observed a non-linear or quadratic relationship between σ and T at temperatures more typically used for frozen products. Wang and Sastry (1993) conducted a study on salt infusion into vegetable tissue prior to ohmic heating. They observed when salt concentration exceeded 0.01 g/cm^3 (1%) in potato tissue, it gave a strong effect on electrical conductivity with the σ-T relationship develop into non-linear (quadratic).

2.2.8.6. Effect of voltage gradient

Halden *et al.* (1990), Palaniappan and Sastry (1991a) studied the effect of voltage gradient on electrical conductivity for several solid food samples. As shown in Figure 2.5a (Sastry and Palaniappan, 1992; Marcotte, 1999) at lower voltage-gradients, the electrical conductivity profile as a function of temperature becomes sigmoidal with a sharp transition around 60°C. It is also possible to obtain sigmoidal curves during conventional heating conditions which would represent a field gradient of approximately 0 V/cm. At higher voltage gradients, the electrical conductivity of solids varies linearly with temperature. Palaniappan and Sastry (1991a) revealed decreasing electrical conductivities of solid food pieces with decreasing voltage gradient, notably at 20°C. They also attempted to explain the reasons for the varying shape of the curve with increasing applied voltage. This occurrence was attributed to applied 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.

Crow (1979) found no measurable variation in electrical conductivity with the voltage gradient when applying a few volts to electrolytic solutions; but observed some differences at 100V/cm. Palaniappan and Sastry (1991b) reported that there was no effect of voltage gradient (30-60V/cm) on the electrical conductivity of orange juice which is a low viscosity fluid. Yongswawatdigul *et al.* (1995b) reported that in surimi high salt concentration (3-4%) must exist to observe an effect of voltage gradient on electrical conductivity.

2.2.9. Ohmic Heating of Foods

Plant foods such as fruit and vegetable are built up by individual cells isolated by the cell membrane and wall. The cell membrane mainly consists of phospholipids and can be regarded as an electrical condenser. The increase of applied voltage induces a membrane potential greater than 1V, and causes pinholes to be created due to a potential discharge. This takes place within a very short time (micro-seconds). This phenomenon of electroporation is well documented in the papers on cell genetic transformation (Tsong, 1990), microbial inactivation

(Hulsheger *et al.*, 1983) and equipment design for extending the shelf life of liquid foods (Dunn and Perlman, 1987; Bushnell *et al.*, 1991). Due to osmotic pressure, the surrounding water will enter the cell and will expand and rupture. The observation of electroporation has mainly been seen under direct current. However, Uemura and Naguchi (1995) found that the length of electrode polarity is sufficient to cause induced membrane potential and subsequent electroporation processed under AC at a high frequency (10 kHz).

Imai *et al.* (1995) determined that electroporation of the radish tissue membrane caused the initial rapid heating (until 50°C) at low frequency (50Hz). A measurement of the impedance after ohmic heating was taken at 50Hz with a 40V/cm field gradient for 10, 30 and 50 s with negligible heat effects. There was a considerable reduction of impedance. A similar result for beet root after ohmic heating of 50 Hz was reported by Halden *et al.* (1990).

Due to molecular diffusion, electro-osmosis occurs in the AC field. During electroblanching, moisture changes in potato slices were enhanced (Wigerstrom, 1976). This presence of an electrical field has been found to produce additional effects such as mass transferring in foods. The loss of cell rigidity and intercellular adhesion may be caused by the dissolution of protopectin and other cell wall constituents such as hemicellulose and will effect food electrical conductivities. This may lead to cell lysis due to the increasing of membrane stress. It can cause a higher level of conductivity due to the breakdown of cellular arrangement which lead to increased ionic mobility increased. Changes in electrical conductivity have been noted 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). Athoyde 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 electro-hydrodynamic mixing. Electrical properties of liquids are affected by the nature of ions (chemical composition), ionic movement and the viscosity of the liquid. All of these depend on temperature (Palaniappan and Sastry, 1991b; Marcotte, 1999).

2.2.9.1. Gel foods

The effect of ohmic heating on fish protein gel was studied by Park *et al.* (1995). The structure of the gel was examined using scanning electron microscopy. As well, the breaking strength and color 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 indicated that there was a significant dielectric loss in the gel. Corrosion of aluminum electrodes increased at 50 Hz with increasing NaCl concentration. There was a negligible contamination of aluminum ions in the product as the frequency was increased to 50 kHz.

Another study was performed by Wang and Sastry (1997b) on the effect of ohmic heating on starch gelatinization. Corn and potato starch suspensions were prepared with an appropriate amount of water (1:5 w/w) and heated at 20 V/cm voltage gradients up to 90°C. The suspensions were evaluated in different stages: pregelatinization, partial gelatinization and complete gelatinization. Endothermic gelatinization peaks were found in both DSC thermograms and electrical conductivity curves as a function of temperature. The DSC thermograms determined the percentage of starch gelatinization. There was good correlation between the low and mid-gelatinization and σ-T curves. It was reported that higher ohmic heating rate probably caused a higher percentage of gelatinization. These observations indicate the potential of quantifying starch gelatinization using electrical conductivity changes, and show the possibility of using an ohmic heating device as an on-line sensor to monitor gelatinization occurring in food processing. Furthermore, electrical conductivity during ohmic heating was found to increase with temperature, but decrease with degree of gelatinization.

2.3. FINE HAM EMULSION

According to Becher (1957), "An emulsion is a heterogeneous system consisting of at least one immiscible liquid intimately dispersed in another in the form of droplets whose diameter, in general, exceeds 0.1 micron". Fine ham emulsion is a two-phase system consisting of a fairly coarse dispersion of two immiscible liquids one being dispersed in the other. Thus, the term "emulsion" is somewhat a misnomer because a meat emulsion is more appropriately described as a complex gel filled with emulsified fat in a matrix of particulate matter consisting of coagulated protein, insoluble myofibrillar fragments and other cellular organelles (Hanson, 1960; Helmer and Saffle, 1963). This complex matrix may also contain other ingredients such as salts, sugar, and non-meat proteins. It is stabilized by its water-binding, gelation and fat-binding properties, even at extreme temperatures. Ordinarily, water and oil are not miscible, but once mixed in the presence of an emulsifier, they can be made to combine into a stable mixture known as a colloidal suspension. These two phases of emulsion are known as: 1) continuous and 2) discontinuous or disperse. During preparation of a fine ham emulsion, solubilized proteins and water form a matrix that encapsulates globules of fat. Fine ham is an example of oil-in-water emulsions, with fat forming the discontinuous phase, water forming the continuous phase, and solubilized meat proteins acting as emulsifiers. To generate a stable emulsion, it is important to dissolve or solubilize the proteins which will act as emulsifiers. Once the protein solution has been prepared, meat fat is comminuted in the presence of protein. Meanwhile, solubilized protein dispersed in the continuous phase coats the fat globules. Fat globules in raw emulsions have a distinct protein membrane encapsulating them. During cooking, the fat unaffected by the heat generated during comminution, is melted but held within limits by the protein membrane. After cooking, the membrane surrounding the fat globules is highly disrupted, and protein of the continuous phase is coagulated in dense, irregular zones (Bard & Townsend, 1978).

2.3.1. Finely Comminuted Meat Products

The various finely comminuted meat systems, such as frankfurters, Vienna sausages, mortadellas, luncheon meat, chicken sausages, and liver sausages, are commonly indicated as meat emulsions (Jones and Mandigo, 1982). These products are generally prepared by chopping or grinding meat with water or ice, salt, and frequently phosphates to a cold meat slurry, then forming the matrix in which the animal fatty tissue and possibly connective tissue material is dispersed. In general, the final temperature during processing does not exceed 15-18°C. Often flavorings, binders, or other additives are mixed in. The stability of finely comminuted meat products is determined by the quality of the meat cuts used (Jones and Mandigo, 1982).

2.3.2. Meat Ingredient

The most desired meat tissue is lean skeletal meat which is obtained mainly from leaner cuts of pork. For a food to be classified as meat, the tissues must be striated muscle of skeletal origin. Different animal tissues will vary in moisture, fat, protein and amounts of pigment. The type of protein, collagen or myofibrillar, is also important. These proteins will vary in their binding properties. Meats considered to have high binding properties are lean skeletal tissues from hogs (Rust, 1987). The general composition of lean meat is 72% water, 21% protein, and 3.7% fat (Macrae, 1993).

Lean meats contribute greatly to emulsion stability and the physical properties of the finished product. During preparation of comminuted meat emulsions, meat proteins serve two functions: to emulsify fat and to bind water. If either of these is not accomplished properly, emulsions will be unstable and subject to breakdown during cooking.

The most ubiquitous of all proteins in an animal is collagen, the predominant protein of connective tissue. The presence of excessive collagen in most sausages is undesirable. For all practical purposes, collagen is not soluble, and when heated to 60 to 65°C in the presence of moisture, collagen fibers shrink to about one-third of their original length. Upon continued heating to temperatures in excess of 65°C, collagen is transformed to gelatin. However, the specific conversion temperature is related to the age of the animal as well as the specific muscle. Because of the low solubility of collagen and because it shrinks and converts to gelatin upon heating, emulsions formulated with large quantities of collagen are usually of borderline stability. It is usually desirable for a finished product to have not more than 25% of the total protein present as collagen (Rust, 1987).

2.3.3. Nonmeat Ingredients

The basic non-meat ingredients are salt, sugar or sweetener, and nitrite. Phosphates are commonly added in commercial operations. A number of other compounds are also used in curing mixtures, such as sodium erythorbate, and hydrolyzed vegetable proteins.

2.3.3.1. Water

Both meat and non-meat proteins must be extracted and dispersed to function effectively as emulsifiers. Water serves to dissolve water-soluble proteins and to form the brine necessary to solubilize salt-soluble proteins. If sufficient moisture is not present in an emulsion, the potential emulsifying capacity of meats is restricted. Then, water serves as the continuous phase of meat emulsions in which the emulsifiers are dispersed.

During preparation of emulsions in an emulsion cutter or mill, there is generation of heat. Excessive heat tends to destabilize the emulsion. To allow time for proper comminution to occur, crushed ice or cold water is added in order to develop sausages with desirable textural characteristics. Added moisture also serves to impart necessary flow characteristics to emulsions. High viscosity emulsions are more prone to physical disruption during processing than similar emulsions of lower viscosity. This factor has become more important with the increased automation of production facilities (Price and Schweigert, 1987).

2.3.3.2. Salt

Salt is the most common non-meat ingredient added to fine meat emulsion product. Each batch of produce produced contains from 1-5% salt, which serves the functions of giving flavor, preserving, and solubilizing proteins. The amount of salt used in fine meat emulsion products varies depending on geographical location and the preference of individual fine meat emulsion product processors. The vast majority of cooked fine meat emulsion products contain 2-3% salt (Kramlich *et al.*, 1973).

Salt serves as a preservative by retarding bacterial growth, thereby functioning as a bacteriostatic rather than bactericidal agent. Bacteriostatic effectiveness is dependent on brine concentration in the fine meat emulsion product and is not a function alone of the total salt present. A 4-5% brine is generally sufficient to preserve properly handled fine meat emulsion products. The ability of salt to solubilize muscle proteins is of vital importance to the successful manufacture of fine meat emulsion product (Schmidt, 1986).

2.3.3.3. Sweetening agents

Sugar is a common substance employed in the curing mixture. Sucrose and glucose are the most commonly used sugars. Other sugars have been used with equal success. Their main functions are flavoring and reduction of the harshness of the salt. The importance of sugar as a flavoring ingredient in cured meats has been diminished somewhat by the change from a heavily salted, stable product to a mildly cured product (Price and Schweigert, 1987).

2.3.3.4. Sodium phosphate

Phosphates are added to the cure to increase the water-binding capacity and thereby the yield of finished product. The action of phosphates in improving water retention appears to be twofold: (1) raising the pH and (2) causing an unfolding of the muscle proteins, thereby making more sites available for water binding. Only alkaline phosphates are effective for improving water binding since acid phosphates may lower the pH and cause greater shrinkage. It also accelerates development of cured color in rapid processing of comminuted meat emulsion product (Pearson and Gillett, 1996).

2.3.3.5. Sodium erythorbate

The two primary reactions that occur after the curing ingredients are introduced into the meat are a reduction of metmyoglobin to myoglobin and a reduction of nitrite to nitric oxide. The nitric oxide is then available to combine with myoglobin to form nitroso-myoglobin. These reactions can be in order to shorten curing times by adding a strong reducing agent. The most frequently used compound is sodium erythorbate. Erythorbate accelerates the conversion of metmyoglobin and nitrite to myoglobin and nitric oxide and also suppresses the reverse reaction. This results in a more complete conversion of the muscle pigment to the cured pigment form. Residual amounts of erythorbate will also add stability to the cured meat pigment by reducing the deterioration of the nitroso-hemochrome and thus giving the color a longer stability (Rust, 1976).

2.3.3.6. Hydrolyzed vegetable proteins

Pearson and Gillett (1996) stated that amino acids in the presence of sugars are known to produce meat flavor aromas. For example, glycine in combination with fructose, maltose, or sucrose gives a beef broth aroma. Glutamic acid combined with glucose or fructose has a chicken-like aroma. Maltose and glycine imparts a baked ham aroma, while lysine with sucrose gives a boiled meat aroma. During neutralization following hydrolysis, salts are also formed that enhance the flavor.

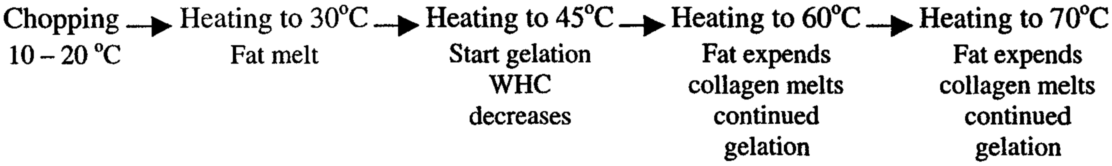
2.3.3.7. Sodium nitrite

Nitrites are the “curing” ingredients added to make cured type of comminuted meat emulsion products. The development of the red or pink cured color (Fig 2.6) is their most recognizable effect. Beside of the color role, nitrites perform other very critical functions in cured meats. They have a pronounced effect on flavor: without nitrites a stale, warmed-over taste would develop in some products. They further affect flavor by acting as powerful antioxidants.

The bacteriostatic properties of nitrites are also critical in cured meats. Sodium nitrite is a very effective inhibitor of the growth of the *Clostridia*, particularly *Clostridium botulinum*, the bacteria that causes botulism. Nitrites provide the ultimate source of the nitric oxide that combines with the myoglobin pigment. About 50 ppm of nitrite in the finished product is usually considered necessary for the formation of the cured color, depending on the actual amount of pigment available to react with the nitrite (Rust, 1976).

2.3.4. Effect of Heat on Fine Ham Emulsion

When the heat is applied to the comminuted meat product, numerous changes take place (Barbut, 1999):



During the initial chopping stage, a flowable product with a paste-like texture is formed (i.e. the product can be moved by a pump). Later on, during the initial cooking process, the fat gradually melts and turns into liquid (Townsend *et al.*,

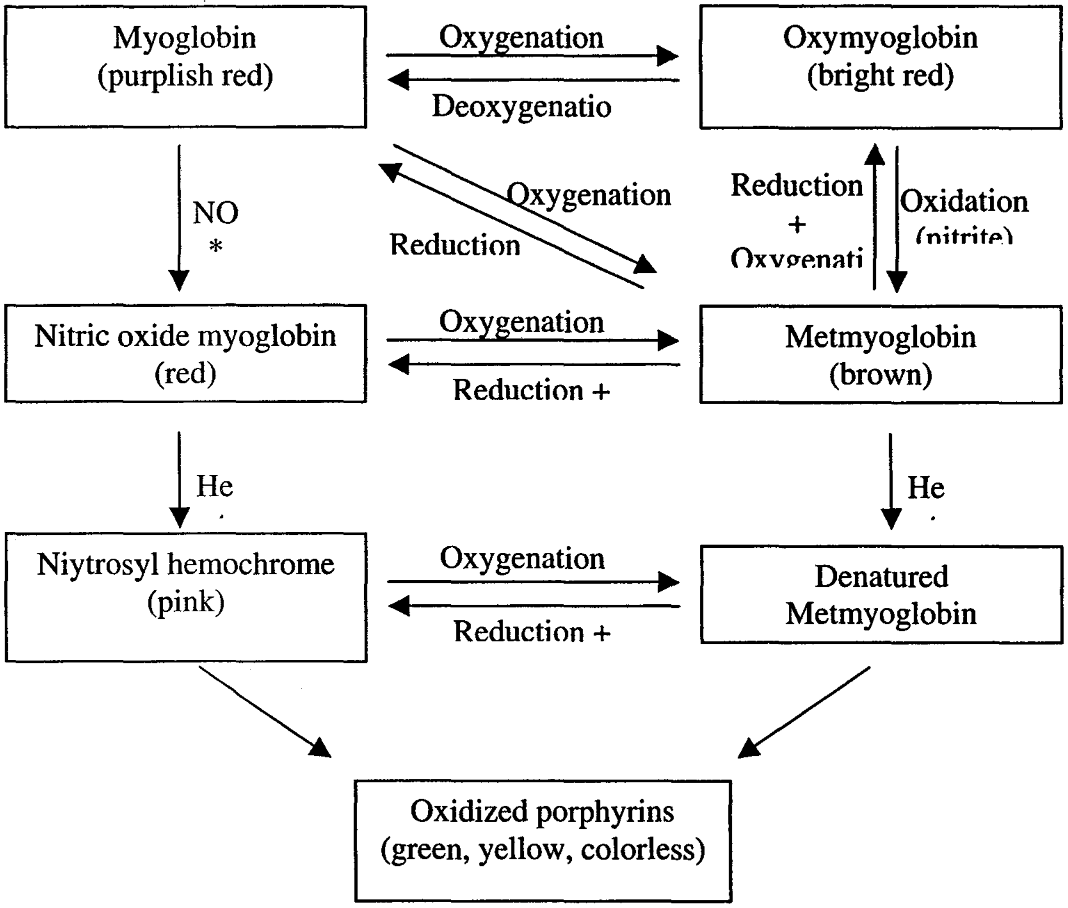


Fig 2.6 Chemical changes of myoglobin that may occur during the curing reaction NO* = Nitric oxide (Price and Schweigert, 1987).

1968).

Myofibular protein denaturation and gelation starts at a later point (Samejima *et al.*, 1976; Barbut *et al.*, 1996) and causes a reduction in the water holding capacity of the proteins (Shults *et al.*, 1972). At this point, the melted fat starts to expand, collagen is transformed into gelatin (i.e. viscous liquid form) and the salt soluble proteins (mainly actin and myosin) continue to form a more elastic gel. The final texture, resulting from cooking to 70 to 75°C, is semi-rigid product (i.e., product does not flow) because the salt soluble proteins have been denaturated and set. Based on the points mentioned so far, today there is more support for the notion that fat stabilization is a combination of the ability of proteins to form an interfacial film, as well as the formation of a gel matrix which physically restricts the movement of fat (Acton *et al.*, 1983; Gordon and Barbut, 1997; Barbut, 1999).

2.3.4.1. Texture development

In emulsion type of foods, the desired mouthfeel is achieved by careful selection of the type of emulsifying agent and stabilizer and by control over homogenization conditions. The texture is determined by the composition of the food, the homogenization conditions and post-processing operations such as heating or freezing. Meat emulsions are oil-in-water (o/w) emulsions in which the continuous phase is a complex colloidal system of gelatin, proteins, minerals and vitamins, and the dispersed phase is fat globules (Fellows, 2000). The stability of the continuous phase is determined in part by the water-holding capacity and fat-holding capacity (Laurie, 1985).

The quality of the emulsion is influenced by 1) the ratios of meat : ice : water : fat, 2) use of polyphosphates to bind water, and 3) the time, temperature and speed of homogenization. The emulsion is set by heat during subsequent cooking. Development of a gel texture exhibiting proper hardness and cohesiveness depends on the gel matrix geometry, flexibility of the polymer and the strength of the junctions (chemical nature and extent of polymer-polymer interactions) (Hermansson, 1988).

2.3.4.1.1. Gelation (protein-protein interaction)

Heat-induced gelation properties of myosin and actomyosin in forming a protein matrix which surrounds emulsified fat is largely responsible for the structural stabilization of the comminuted meat system following heating (Hanson, 1960; Helmer, 1963; Schut, 1976; Acton *et al.*, 1983). Binding strength is dependent upon the amount of myosin and actomyosin released from the meat structure by the processing method used. The amount and kind of salts, the degree of mixing, tumbling, massaging or blending prior to salt formation and gelatinization by heating (Acton and Dick, 1984).

Studies by Yasui *et al.* (1982) and their previous work confirm that gelation in comminuted meat products is specifically related to the physico-chemical properties of myosin to synthetic actomyosin. The regulatory proteins did not affect the heat induced gelation of myosin in the presence of actomyosin. Acton and Dick (1984) discussed protein-protein interactions in meats and described gelation as an ordered protein-protein interaction of myosin which is denatured to form the well ordered structural matrix surrounding emulsified fat. Denaturation is usually considered to be a physical process which alters the molecular alignment, the conformation and the degree of folding of a protein. This allows more reactive sites to become exposed for binding of water and other protein (Bailey, 1989). From the above discussion, it is obvious that gelation in meat systems is largely dependent on the concentration, solubility and degree of denaturation of myosin. As processing temperatures increase (30 to 50°C), considerable reduction of SH groups occurs in the myosin head. This indicates the formation of covalent bonds as an early step in myosin protein-protein binding (Samejima *et al.*, 1981), despite the fact that hydrophobic interactions are generally believed to be more important than covalent bonding in the head to head aggregation of myosin. A higher degree of intermolecular bonding also occurs at increased temperatures (60°C) where unfolded, randomly coiled polypeptides interact to form a gel matrix which can be observed under the scanning electron microscope (Yasui *et al.*, 1982). The overall process requires the aggregation of rods to proceed slowly. This allows the denatured proteins time to become oriented and to interact at specific points to form a complex network (Hermansson, 1984).

The gel strength of myosin and its subfragments is largely a function of temperature and reaches its maximum at 60°C (Samejima *et al.*, 1981), but it is somewhat dependent upon pH, ionic strength and protein concentration.

2.3.4.2. Color development

Cooked comminuted meat emulsion color is developed through a process known as emulsion curing; a process generally used when nitrite is included in the curing formula. Sodium nitrate is added to the bowl cutter along with the lean meats. The development of maximum cured meat color is achieved by adding sodium erythorbate. Conversion of meat pigment to cured meat pigment is a function of time, product temperature, and presence of oxygen. Cured color development in comminuted meat emulsion is significantly impeded at cooler temperatures but proceeds with increasing rapidity as comminuted meat emulsion temperature increases during cooking (Kramlich, 1978).

2.3.4.3. Water holding capacity

The ability for comminuted meat emulsion products to hold considerable amounts of water is determined by the extent to which the bulk of the water is immobilized or entrapped within the microstructure of the intact or comminuted tissue. It is now known that protein gelation and entrapment of constituents rather than emulsification of fat is the primary determinant of product stability and texture in meat batter (Gordon and Barbut, 1992; Barbut, 1996). When muscle is comminuted with salt, the muscle cell walls (sarcolemma), which sheathes the myofibrils, is destroyed. Thus, the constituent myofilaments are no longer restrained and the myofibrillar system is transformed form one of limited swelling to one of unlimited swelling accompanied by an increased water holding capacity (Honikel and Hamm, 1994). The final result of thermally induced unfolding and aggregation of muscle proteins is a heat-set protein gel matrix that provides suitable texture, water-holding and fat-holding (Foegeding, 1989).

2.3.4.4. *Water activity*

Water in food exerts a vapour pressure. The level of the vapour pressure depends on the amount of water present, the temperature and the concentration of dissolved solutes (particularly salts and sugars) in water. Water activity is defined as "the ratio of the vapour pressure of water in a food to the saturated vapour pressure of water at the same temperature"; the equation is expressed as:

$$WaterActivity = \frac{P}{P_0} \qquad [2.17]$$

where P (Pa) = vapour pressure of the food, P_0 (Pa) = vapour pressure of pure water at the same temperature (Fellows, 2000).

The effect of water activity on foods is a very important factor in controlling the rates of microbial and enzymic deterioration (Lewis, 1990). Almost all microbial activity is inhibited below $a_w = 0.6$, most fungi are inhibited below $a_w = 0.7$, most yeasts are inhibited below $a_w = 0.8$, and most bacteria are inhibited below $a_w = 0.9$. Enzymic activity virtually ceases at a_w value below the Brunauer-Emmett-Teller monolayer value (Fennema, 1996) when the water within a food system is strongly bound to specific sites such as hydroxyl groups of polysaccharides, carbonyl and amino groups of proteins, and hydrogen bonding (Fellows, 2000).

2.3.4.5. *Cooking loss*

Cooking loss is defined as release of fluid after heating of meat or meat products without application of external forces, e.g. centrifugation or pressing (Hamm, 1983). Cooking losses result from the melting of fat that form evaporated drippings of water, and other volatiles. When meat is cooked in an open container, considerable evaporation of the water from the surface of the meat occurs. Fat losses that occur are less consistent due to the uneven distribution of fat throughout the meat. Fat that is located close to the surface will be lost faster than that found in the interior of the meat; however, the surface fat layer aids in decreasing water loss due to evaporation (Resurreccion, 1994).

CHAPTER 3

KINETICS OF QUALITY CHANGE UNDER CONVENTIONAL HEATING CONDITIONS

3.1. ABSTRACT

The kinetics of change in quality parameters (color, texture, water holding capacity, cooking loss, and water activity) associated with conventional heating of fine ham emulsions were evaluated. Samples (~30g) of raw fine ham emulsion, prepared according to an industry formulation, were sealed in transparent plastic tubes. These were subjected to a range of conventional heat treatments (at 50 to 80°C in 5°C increments) in a temperature controlled agitated water bath. Once the target temperature was reached, a range of different holding/cooking times (0-180 min) were used depending on the cooking temperature. Kinetics of quality changes were characterized using various regression models. Higher processing temperatures caused a faster color and texture development. At lower temperatures (≤65°C), color and texture development was nevertheless completed during the extended holding period; while at temperatures ≥70°C, they almost reached their full development by the end of the come-up period. Thus, color and texture development were dependent on both bath temperature and heating time. Kinetic parameters (D and z values) were evaluated from test data based on a first order model ($R^2>0.9$).

3.2. INTRODUCTION

Cooking is a process of thermal treatment, during which chemical, physical and microbial changes occur in food, and generally results in a more palatable product (Paulus, 1984). A knowledge of these changes, and in particular of physical changes, as a function of cooking time and product temperature is necessary for the successful optimization thermal processing of foods (Dagerskog, 1978). With respect to meat emulsion product, such information is useful in designing improved thermal processes, which minimize product shrinkage and maximize their quality attributes. Meat emulsions, such as frankfurters, Vienna sausages, mortadellas, luncheon meat, chicken sausages, and liver sausages, are generally prepared by chopping or grinding meat with water or ice and salt (frequently phosphates), added to the cold meat slurry, then forming a matrix in which the animal fatty tissue and possibly connective tissue is dispersed. When heat is applied to these products, several changes take place (Barbut, 1999) starting from the melting of fat, solubilization and denaturation of myofibrilar proteins, transformation of collagen to gelatin, reduction in the water holding capacity of the proteins and finally the formation of an elastic gel matrix.

The formation of meat emulsion quality is a complex process as it is influenced by a multivariate system of physico-chemical parameters. The sensory and other quality attributes result from the natural structure of food elements, their mutual arrangement, interaction and manner in which they are perceived by the human senses (Bourne, 1982; Klettner, 1994; Tilgner, 1979). The physical quality parameters of color, texture, water holding capacity, cooking loss and water activity play a significant role in the quality acceptance of meat products. Cooking conditions determine to a large extent what kind of molecular associations (protein-protein) occur during the gelling process of the meat emulsion (Foegeding *et al.*, 1986; Camou *et al.*, 1989; Carballo *et al.*, 1996). Thermal transitions of the fat and protein during cooking and cooling helps to fix the interfacial protein film and gel matrix. This entraps both water and fat, and is primarily responsible for the texture of meat emulsion. The matrix further stabilizes the fat in the meat emulsion (Pearson and Gillett, 1996).

Several studies have reported that during thermal processing, factors such as heating rate and/or profile, final temperature or holding time can determine a number of aspects of the final quality (texture, color, cooking looking, water holding properties, and etc.) of meat products (Monagle *et al.*, 1974; Singh *et al.*, 1985; Foegeding and Ramsey, 1987; Mittal *et al.*, 1987; Barbut and Mittal, 1990; Hunt *et al.*, 1994). Indeed, the desirability of exploring heat processing conditions in the manufacture of low-fat products has been noted by a number of authors (Claus, 1991; Martin and Rogers, 1991; Hull *et al.*, 1992; Pearson and Gillett, 1996; Carballo *et al.*, 1996).

Processing conditions affect a number of properties of meat emulsions such as color (Wirth, 1988; Goutenfongea and Dumont, 1990; Carballo *et al.*, 1996), texture (hardness, elasticity, cohesiveness, etc.) (Singh *et al.*, 1985; Foegeding and Ramsey 1987; Barbut and Mittal 1990; Hunt *et al.*, 1994; Carballo *et al.*, 1996), binding properties (Mittal and Blais-dell, 1983; Puolanne and Kukkonen, 1983; Barbut and Mittal, 1990; Hunt *et al.*, 1994; Carballo *et al.*, 1996), cooking loss (Anjaneyulu, 1989), water holding capacity (Ambrosiadis *et al.*, 2000; Pietrasik and Duda, 2000; Correia and Mittal, 1991) and water activity

(Fennema, 1985; Lee and Styliadis, 1996). The product composition has been shown to affect the final quality of the cooked meat product (Mittal and Blaisdell, 1983; Singh *et al.*, 1985; Wirth, 1988).

The objectives of this study were to evaluate quality parameters such as color, texture, cooking loss, water holding capacity and water activity of fine-ham emulsion subjected to thermal treatment at various temperatures (50-80°C) and obtain pertinent kinetic parameters to describe the thermal effect on quality parameters. The research was aimed at obtaining a database on thermal destruction kinetics of quality parameters in order to provide a basis for comparing the beneficial effects of rapid heating techniques such as ohmic heating on quality of cooked ham emulsions.

3.3. MATERIALS AND METHODS

3.3.1. Meat Emulsion Preparation

Fresh lean ground pork, trimmed of all visible fat (<5% fat content) and connective tissue, was obtained from the local butcher in St-Hyacinthe, Quebec. The ground pork was stored at –40°C in vacuum-sealed packages (1 kg ground meat per package) and filled with an oxygen absorbent sachet (Mitsubishi, Japan). The ground pork was allowed to temper at 4°C for 18 hours prior to formulation and processing.

The brine was prepared the day before the experiment, except for the addition of sodium nitrite. An industrial formulation of brine is summarized in Table 3.1. Sodium nitrite was added to the brine 20 min before the emulsification

Table 3.1 Concentration of brine ingredients in brine solution and raw ham emulsion

Brine Ingredients	Ingredients (%)	
	Brine Solution	Raw Ham Emulsion 65/100 brine/meat
Sodium phosphate	1.27	0.50
Sodium chloride	5.73	2.26
Glucose	2.36	0.93
Sodium erythrobate	0.18	0.07
Vegetable protein hydrolysate	0.64	0.25
Sodium nitrite	0.79	0.31

process began.

A Cutmaster chopper (Stephan, Hameln, Germany) was used for chopping and emulsifying. The industrial formulation used in this study was based on a 65/100 brine/meat ratio. First, ground pork and half of the brine were comminuted for 30 seconds. The remaining brine was added and the comminuting continued for an additional 90 seconds. The temperature of the meat emulsion was carefully monitored so as not to exceed 12°C. A vacuum tumbler (Roschermatic, Osnabruck, W. Germany) was used to eliminate air pockets in the emulsion. The emulsified meat batter was filled into 25 mm diameter water-impermeable open ended plastic tubes, about 75 mm in length, and plugged with stoppers on both ends, weighed and placed in an ice-water bath to minimize chemical changes prior to processing. Duplicate samples were heat treated under conventional water-bath heating conditions in a total of 14 experiments.

3.3.2. Emulsion Processing

Prepared tubes of ham emulsions were heated in a well agitated water-bath (Western Canada, Inc., Calgary, AB) to various internal temperatures ranging from 50 to 80°C in 5°C increments, then held at target temperatures for periods ranging from 0 – 180 min. During the come-up period, the water-bath temperature was held ~2°C higher than the pre-selected final internal cooking temperature to ensure reaching the desired temperature in about 20 min. Internal temperature was monitored using a T-type thermocouple (Omega Engineering, Inc., Stamford, CT) inserted along the axis of the sample tube. A temperature-measuring system consisting of a PC, a data logger (Fluke Corportation, Everett, WA) and thermocouples, served to record internal temperatures at 5 seconds intervals. When the heat treatment was completed, test tubes were immediately immersed in an ice-water bath, to avoid additional after heat effects, and stored at 4°C overnight.

3.3.3. Measurement of Quality Parameters

3.3.3.1. Color

The color of test samples was measured using a tristimulus color analyzer (Chroma Meter II Reflectance Meter, Minolta Corporation, Ramsay, NJ) utilizing Illuminant $D_{65.}$ The instrument was calibrated against a Minolta standard-white reflector plate. Hunter-Lab L* (light-dark), a* (red-green), and b* (yellow-blue) values were determined for each treatment. Three 25 mm thick slices were cut from each of the two replicate samples. The L*, a* and b* color parameters were measured both on the exterior surfaces and the internal cut surfaces in the central region. At least 8 readings were taken on both exterior and internal surfaces and the readings were averaged for estimating the L*, a* and b* values. The mean values from the external surface were designated as "surface color" values while those from the internal cut surface near the centre were designated as "internal" color values.

3.3.3.2. Texture

A texture profile analysis (TPA) test (Bourne, 1982) was carried out using a Texture Analyser 2xi (Stable micro systems, Surrey, England). Test samples were cylinders, 25 mm in diameter and 25 mm in length, cut from the meat-emulsion cylinders pushed out of the sample tubes. This test consisted of two consecutive compression cycles, each conducted to 50% of the original sample length. The speed of the cross head was 100 mm/min with a 25 kg load cell. This test was carried out in duplicate. The texture profile parameters, namely hardness, cohesiveness, springiness, gumminess, and chewiness were computed from the manufacturer-supplied software. As detailed in the previous chapter, the following descriptions were given (Szczesniak, 1963) for the different quality parameters: Hardness was defined as the force necessary to attain a given deformation. Cohesiveness was the strength of the internal bonds making up the body of the product. Springiness was essentially the rate at which a deformed material recovered to its original condition after the removal of the deforming force. Gumminess was the energy required to disintegrate a semi-solid food product to a state ready for swallowing. Chewiness was defined as the energy required to masticate a solid food product to a state ready for swallowing. Figure 3.1 shows a typical two-cycle force deformation curve indicating the different parameters used in the computation of textural attributes (Table 3.2).

3.3.3.3. Cooking loss

Cooking loss was calculated using the following formula (McDermott *et al.*, 1999):

$$CL\% = 100\frac{(W_u - W_p) - (W_c - W_p)}{(W_u - W_p)} \qquad [3.1]$$

where:

$CL\%$ = cooking loss (%),

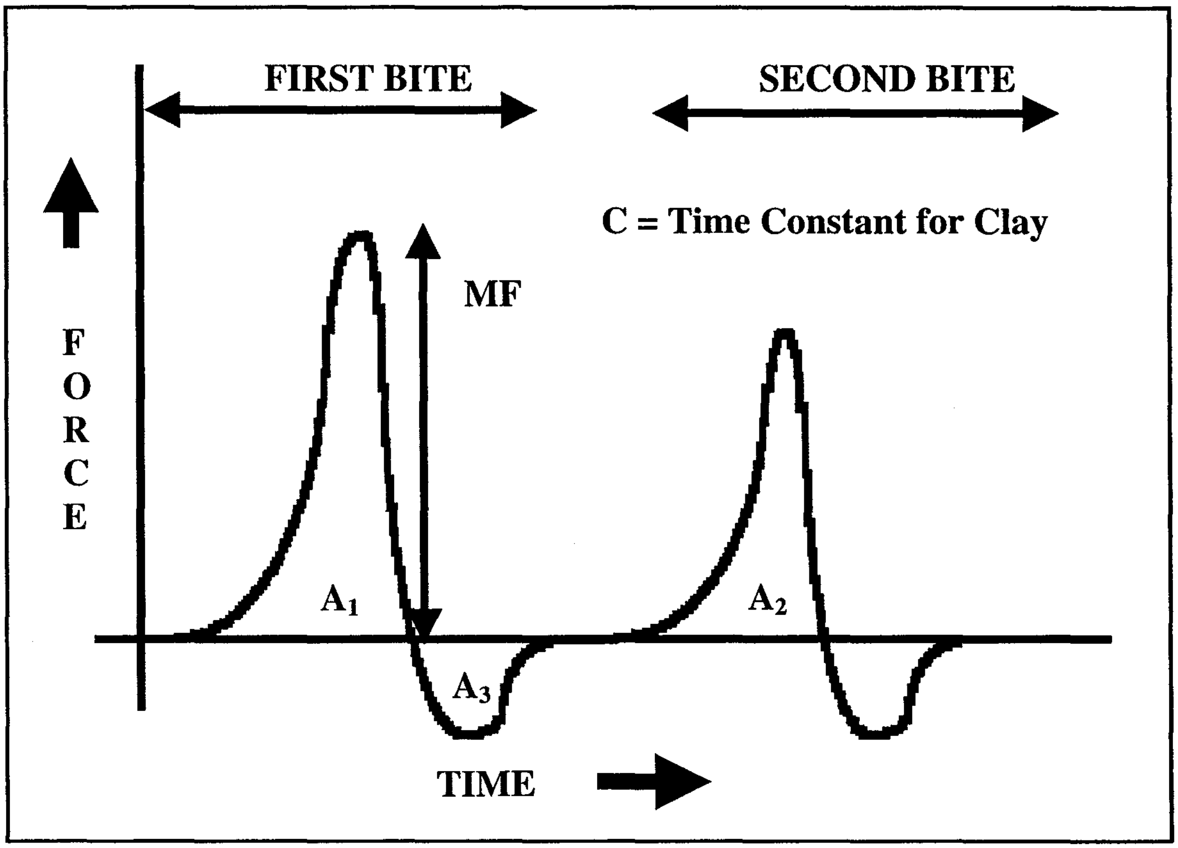


Figure 3.1 A representative graph of the texture curves obtained for the samples
Adapted from: Texture Technologies Corp (2000) at www.texturetechnologies.com/tpa.htm

Table 3.2 Formulas used for computing various textural attributes (Texture Technologies Corp, 2000)

Texture Parameter	Formula
Hardness (N)	Maximum force/A_1
Cohesiveness	A_2/A_1
Springiness	First Bite - C
Gumminess (N)	(Hardness × Cohesiveness)/100
Chewiness (N)	Hardness × Cohesiveness × Elasticity

W_u = weight of the sample + plastic test tube (meat emulsion, tube, clips) prior to processing (kg),

W_c = weight of sample + plastic test tube after processing (kg),

W_p = weight of plastic test tube (casing, clips) (kg). These measurements were carried out in duplicate.

3.3.3.4. Water holding capacity

The drip-free treated sample was ground, and a 30 g ground samples was centrifuged at 35,500 g (17,500 rpm) for 20 min at 4°C. After centrifugation, the supernatant was removed, and the residual sample was weighed. Water holding capacity (WHC) was expressed as the percentage of the initial water content, which remained in the ham paste after cooking, grinding, and centrifugation. This represented the fraction of water, which remained bound within the meat during processing and was obtained using the following formula (Piette *et al.*, 1998):

$$WHC(\%) = 100 * \frac{initial\ water - water\ lost}{initial\ water} \quad [3.2]$$

3.3.3.5. Water activity

Water activity (a_w) of test samples were measured with an AquaLab CX-2 (Decagon Devices, Pullman, WA) at 20°C. For accuracy, the a_w measurement device was calibrated with deionized water to an a_w of 0.999 ± 0.001 at 20°C before use. About 3 g ground sample of the processed product was split into three ~1 g samples for three measurements.

3.3.4 Analysis of kinetic data

Quality changes under thermal processing were assumed to follow first order reaction rate kinetics (Labuza, 1982; Labuza and Riboh, 1983), with a reaction rate constant, k, at a particular processing temperature:

$$k = \frac{-\log\left(\frac{C_{\max} - C_t}{C_{\max} - C_0}\right)}{t} \qquad [3.3]$$

where:

$C_t =$ value of the quality attribute after a given thermal treatment time,

$C_o =$ initial value of the quality attribute,

$C_{max} =$ maximum value (or C_{min}, minimum value) of the quality attribute,

$t =$ time (min), and

$k =$ reaction rate constant (min^{-1}) at a particular temperature, calculated from the absolute value of the slope of the $\log_e [(C_{max} - C_t) / C_{max} - C_o)]$ *vs.* time (t).

The decimal reduction time (D-value) representing the heating time that results in 90% reduction of initial quality at a given temperature was obtained mathematically by,

$$D = \frac{2.303}{k} \qquad [3.4]$$

Temperature sensitivity parameter of the D-value was expressed as a z-value, which represented the temperature range that results in a 10-fold change in D-value:

$$z = \frac{(T_2 - T_1)}{\log\left(\frac{D_1}{D_2}\right)} \qquad [3.5]$$

where :

D_1 and D_2 were decimal reduction times at temperatures T_1 and T_2, respectively. The z value was obtained by linear regression decimal reduction time on log scale *vs.* temperature.

D and z values were initially calculated from the actual (uncorrected) heating time. However, based on time-temperature profiles, the effective heating times (t_e) were calculated for each heat treatment as the accumulated lethality (L *or* t_e):

$$t_e = \int_0^t 10^{\frac{(T-T_{ref})}{z}} dt \qquad [3.6]$$

where:

t_e = effective heating time,

T_{ref} = pre-selected bath temperature for the experiment. D and z values were then re-calculated (Figure 3.2) using the corrected effective heating time (Tajchakavit, 1997). This procedure was repeated several times till the difference of z-values from two successive calculations were within 5%.

3.4. RESULTS AND DISCUSSION

3.4.1. Heating Behaviour

Typical come-up and come-down period temperature profiles under the conventional thermal heating and ice-water cooling condition are shown in Figure 3.3. Examination of heat penetration data from these preliminary runs with thermocouples placed at the geometric centre and near the wall of the plastic cylindrical tube indicated that the heat penetration appeared to occur gradually and fairly uniformly in the well-agitated water bath set at pre-selected water bath

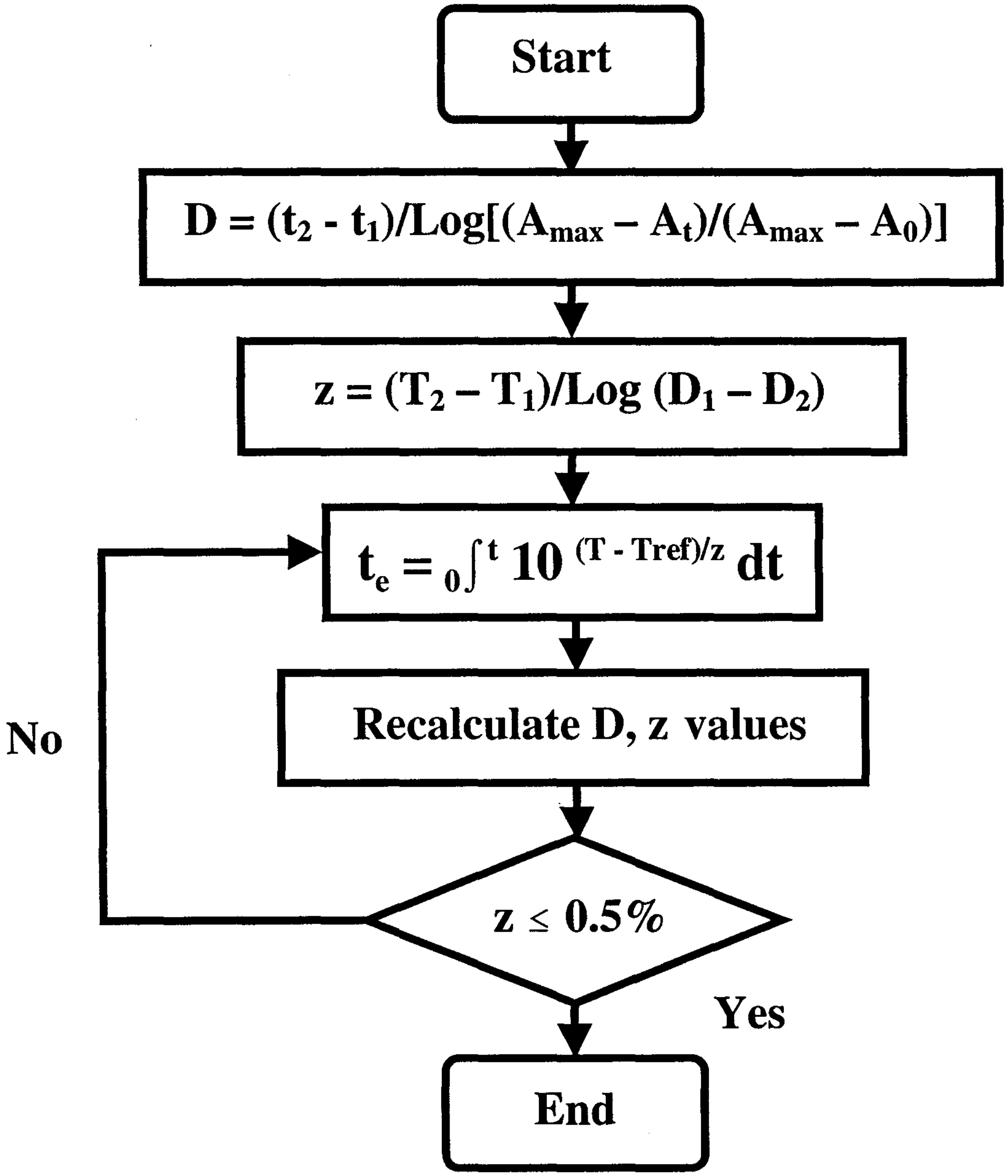
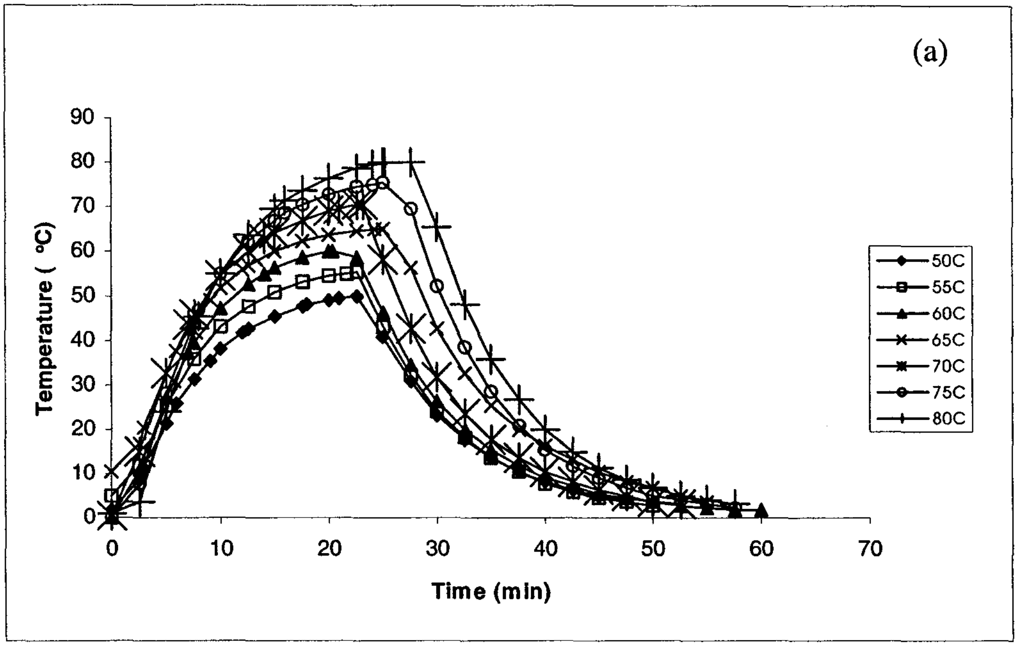


Figure 3.2 Flow chart of calculation steps for kinetic data analysis (Tajchakavit, 1997)



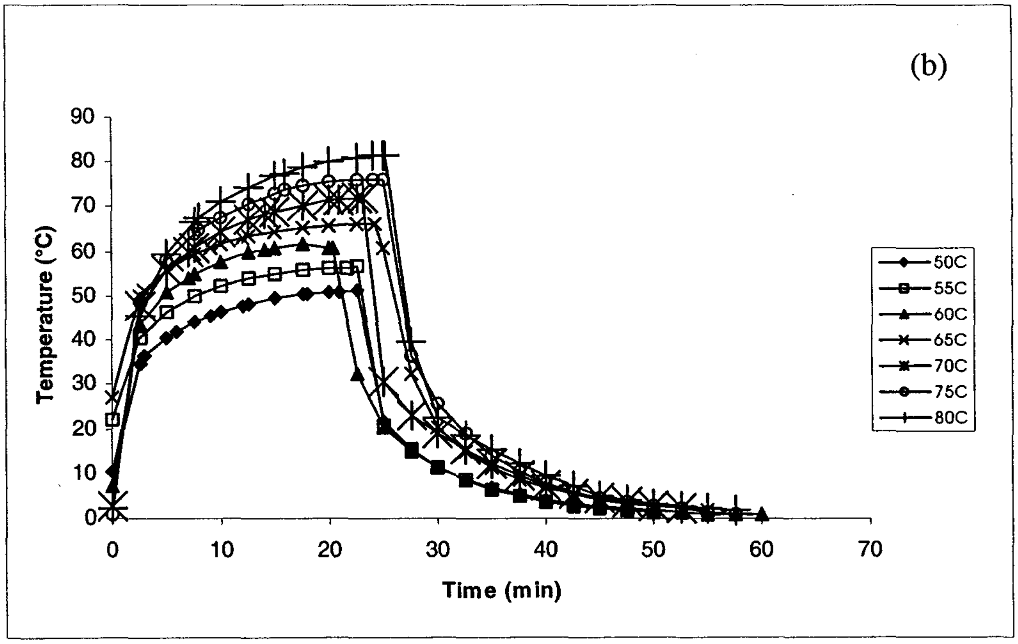


Figure 3.3 Temperature profiles of fine ham emulsion processed at 50-80°C (a) at the center and (b) on the surface

temperature (final temperature + 2°C). Small temperature differences existed, and compared to the thermocouple located near the wall, the one at the geometric centre had slightly lower temperatures during the come-up period (Fig 3.3a) as compared to the one near the surface. The come-up time with reference to the centre was about five minutes longer than the come-up time at the surface. Thus the sample at the surface was cooked for about five minutes extra time as compared to the sample at the centre. These differences were presumed to be responsible for any differences observed between the color on the surface and at the centre, which will be discussed later. The come-up times varied from 20 to 25 min. For the kinetic analyses, the centre point time-temperature profiles were integrated to compute an effective time at the bath temperature.

3.4.2. Effect of Thermal Processing on Quality Attributes

3.4.2.1. Color changes

Figures 3.4 – 3.6 show color development (L*, a* and b* values at the center and surface) in ham emulsion at various temperatures as a function of thermal treatment times. L* values at the surface and internal increased with heating time (come-up and holding times) and temperature, reaching a characteristic maximum at a given temperature. The maximum values were temperature dependent with higher temperatures generally resulting in higher values and shorter heating times. The color values on the surface also reached their maximum at a shorter time than those at the centre, presumably because of the faster surface come-up times. Table 3.3 shows the tabulated values of maximum L* values at each treatment

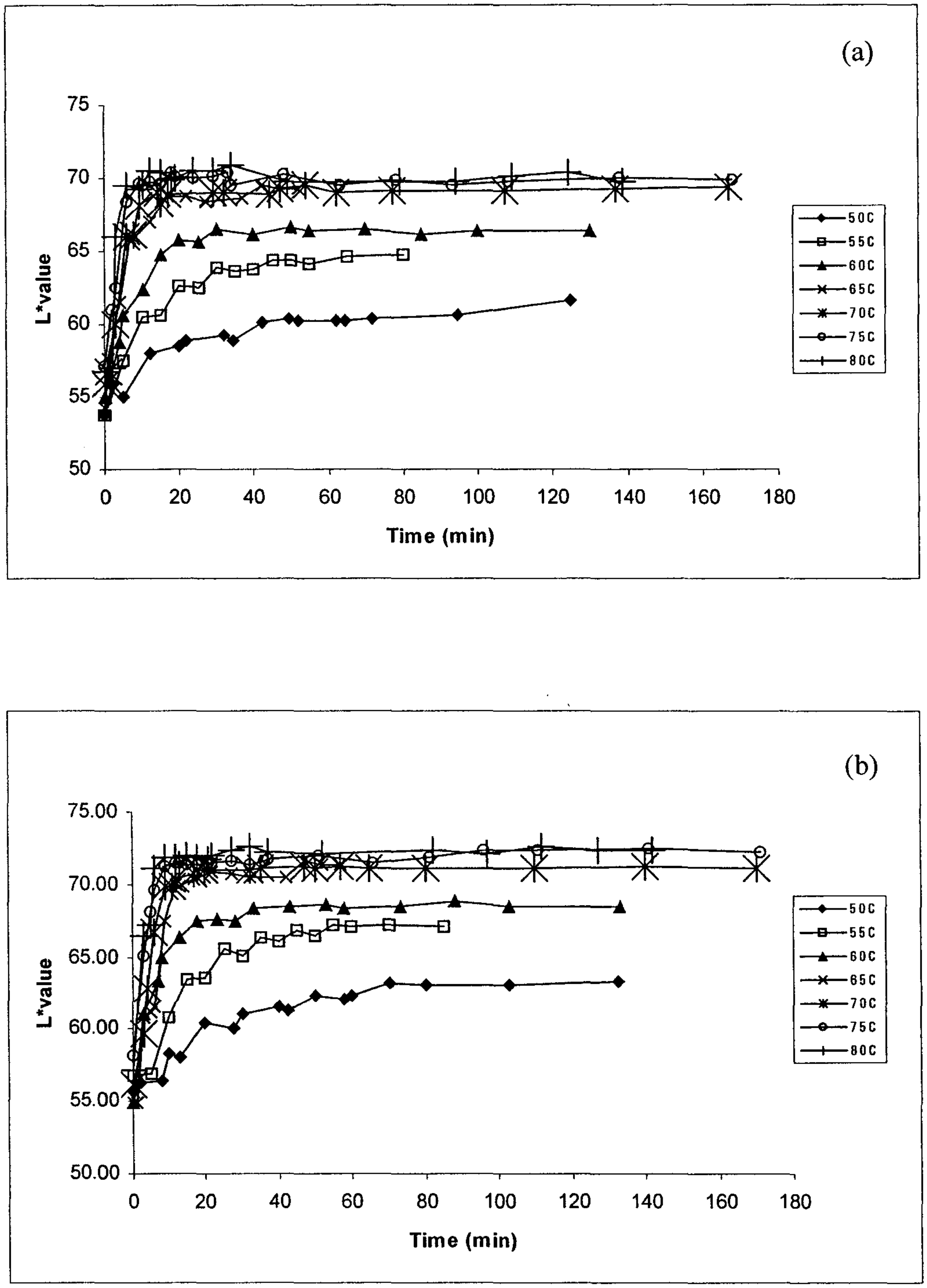


Figure 3.4 Color changes of L* value in fine ham emulsion (a) at the center and (b) on the surface

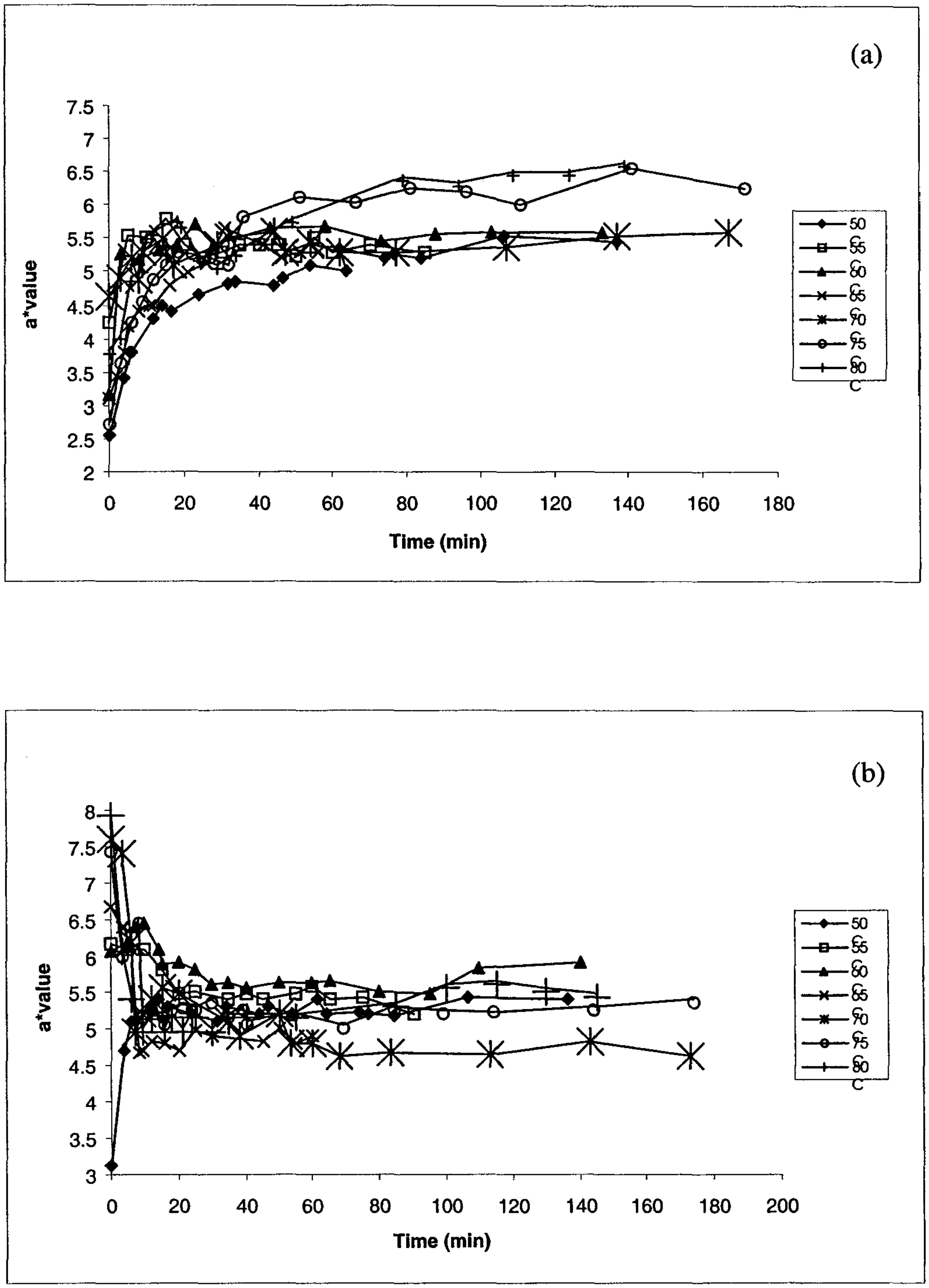
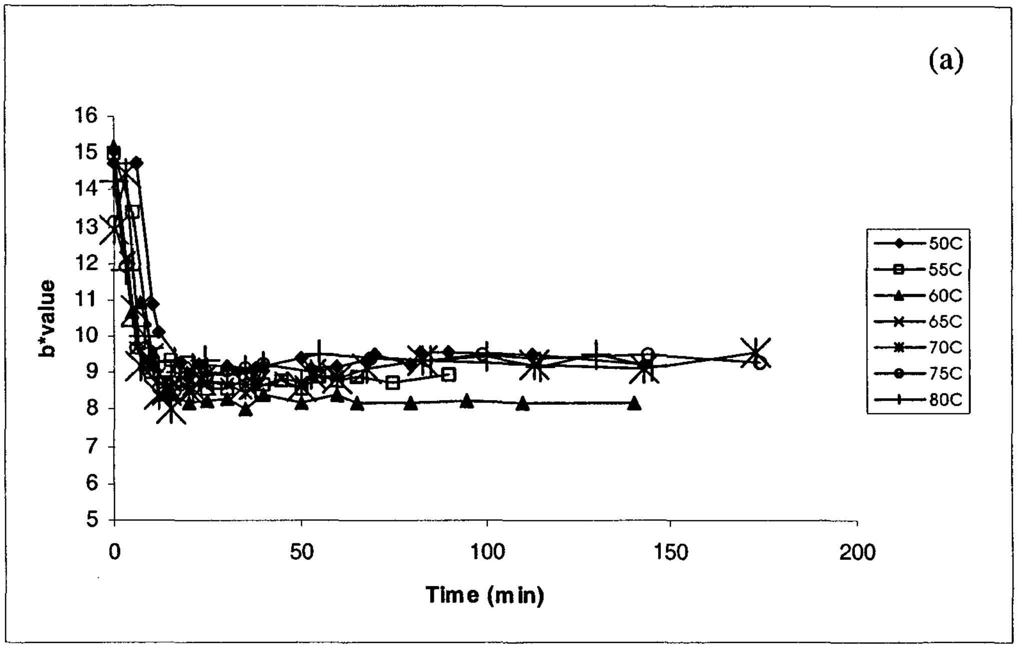


Figure 3.5 Color changes of a* value in fine ham emulsion (a) at the center and (b) on the surface



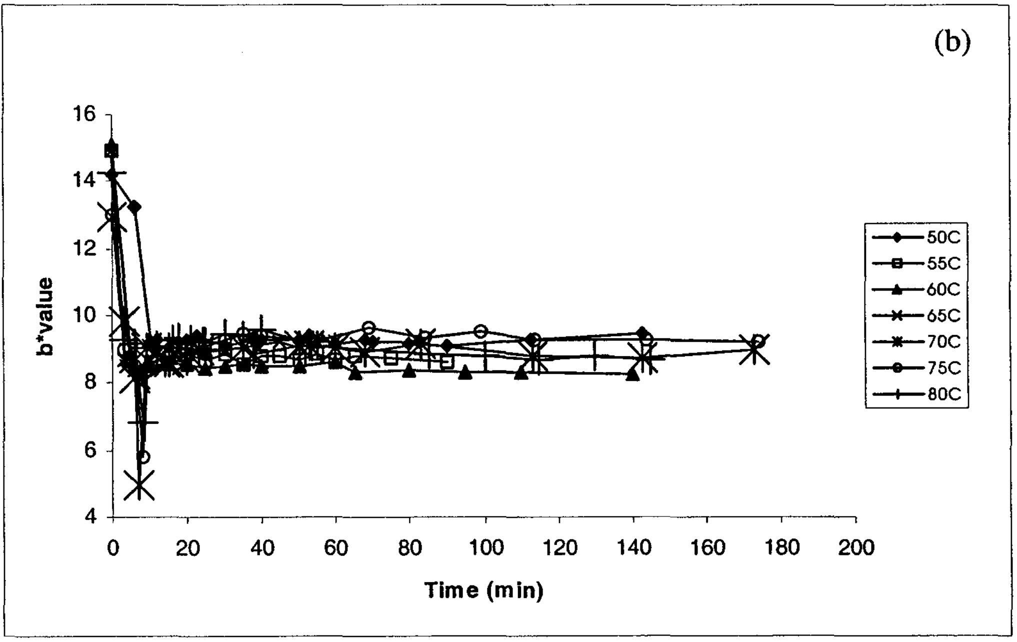


Figure 3.6 Color changes of b* value in fine ham emulsion (a) at the center and (b) on the surface

Table 3.3 Maximum values of color parameters and the minimum time (t_{min}) taken to reach the maximum under conventional heating of ham emulsions at different temperatures (all values are means of two replicates).

Temperature (°C)	Color parameter											
	Surface						Internal					
	L^*_{max}	t_{min} (min)	a^*_{max}	t_{min} (min)	b^*_{min}	t_{max} (min)	L^*_{max}	t_{min} (min)	a^*_{max}	t_{min} (min)	b^*_{min}	t_{max} (min)
50	62.34	70	5.4	14	9.19	60.00	60.17	60	5.38	34.67	9.10	37.67
55	66.41	55	5.5	15	8.70	25.00	63.85	40	5.17	30	8.57	30.00
60	68.39	40	5.9	8	8.41	25.00	65.8	30	5.13	28	8.00	35.30
65	70.00	15	4.68	5	8.41	6.00	67.01	20	4.84	12	8.47	35.00
70	70.37	15	4.95	4	8.60	14.00	68	15	5.48	14	8.00	15.00
75	71.20	12	5.2	5	8.15	6.00	68.35	12	5.47	15	8.50	16.00
80	71.08	9	5	6	9.17	6.00	69.57	12	5.15	12	8.84	12.00

temperature, and the minimum effective time necessary to attain this maximum. L^*_{max} values were slightly higher for the surface color and the associated t_{min} were lower. In fact, at higher temperatures the maximum value was reached within the come-up period. The pattern of color formation was characteristically same both at the surface and the centre. These results are consistent with some previous studies (Koutchma *et al.*, 2000; Piette *et al.*, 1997b). Color changes with respect to a* (the green-red chromaticity values) (Fig. 3.5) showed somewhat similar results with the centre color; however, the results from the surface showed an erratic pattern: some cases demonstrating a decrease to an equilibrium value, while others showing increased values. As shown in Table 3.3, the equilibrium a* values were about 5±0.5 for the surface with no clear indication of the development, hence no further characterization was attempted for this parameter. On the other hand, centre a* values demonstrated a more consistent and a gradual development pattern. A similar pattern was also noticed with b* values. Hence only 4 color parameters were chosen for further analyses (L*- surface, L*- internal, a*-internal, and b*- internal).

In an attempt to characterize the color change kinetics, a first order model was used. Since the color parameter varied between the initial and an equilibrium value (maximum), the kinetic parameters were characterized using a semi-logarithmic relationship [(Max parameter value-Value at time t)/(Maximum parameter value-Initial value) on log scale] vs. effective (corrected) time from which the D values were computed as negative reciprocal slope of the regression lines. Figures 3.7-3.9 show changes in L*-internal, L*- surface, a*-internal, and

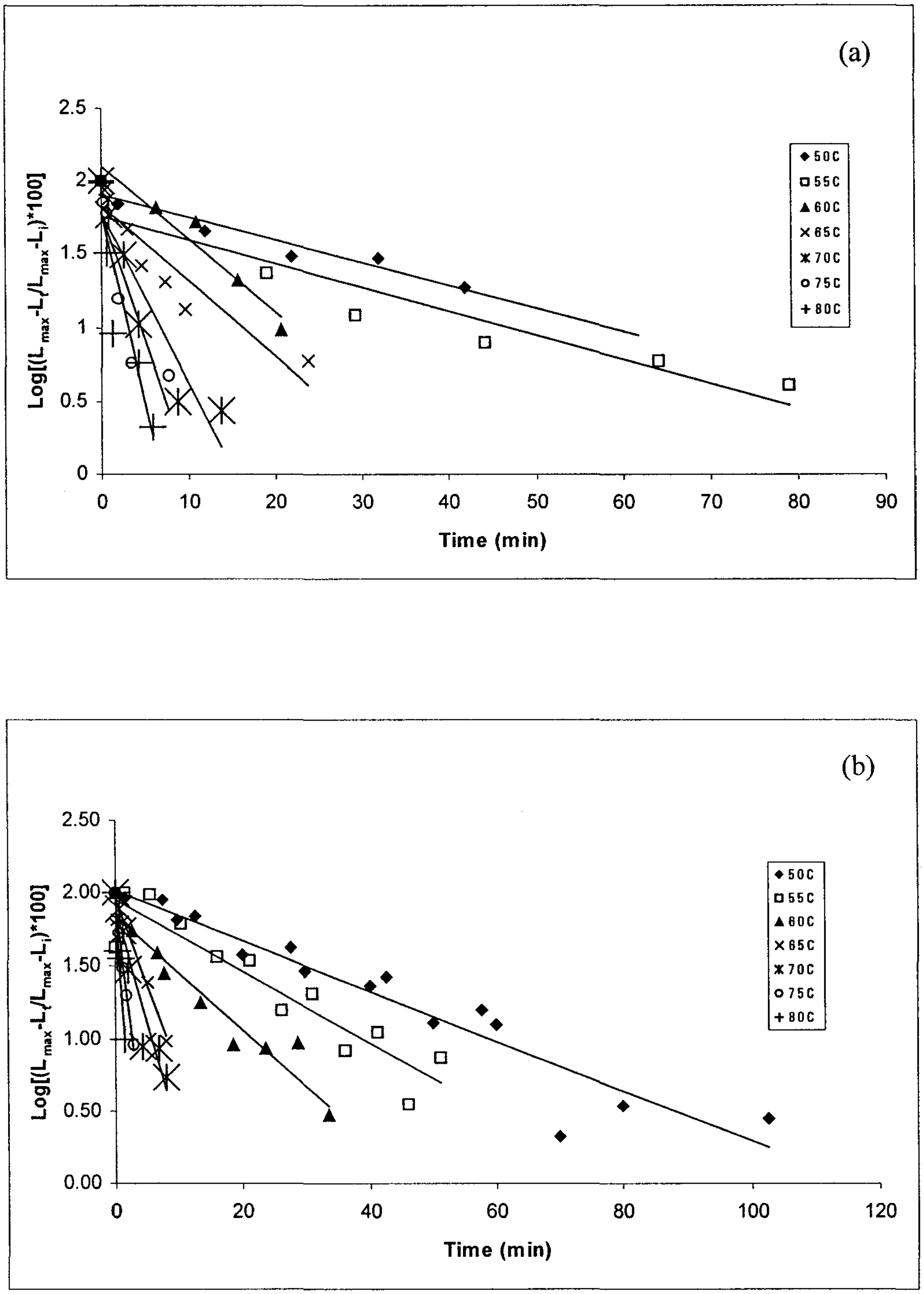


Figure 3.7 Color changes of L* value in fine ham emulsion after time corrected (a) at the center and (b) on the surface

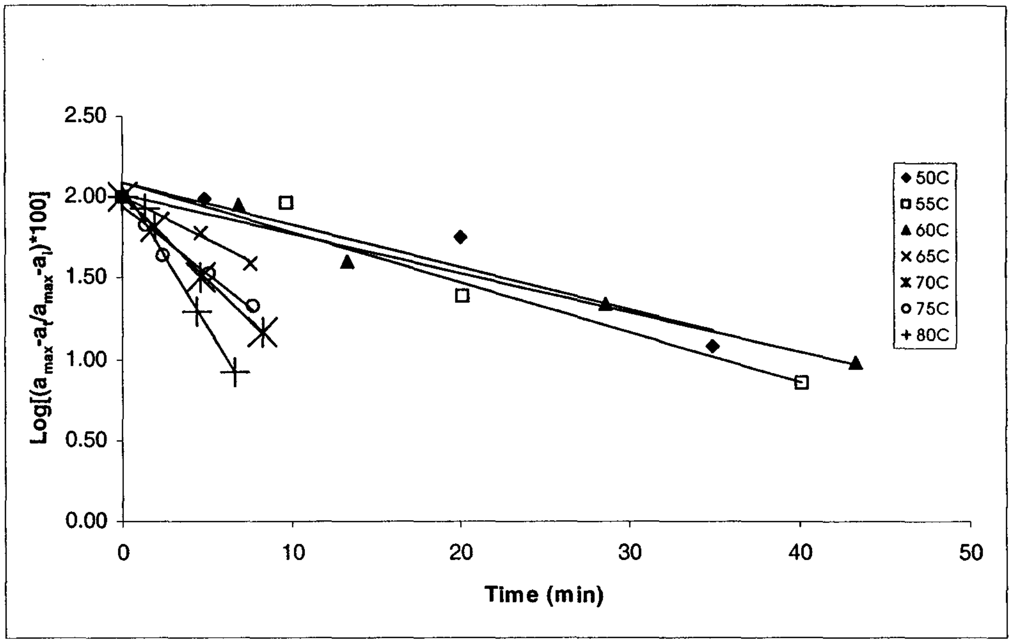


Figure 3.8 Color changes of a* value at the centre in fine ham emulsion after time corrected

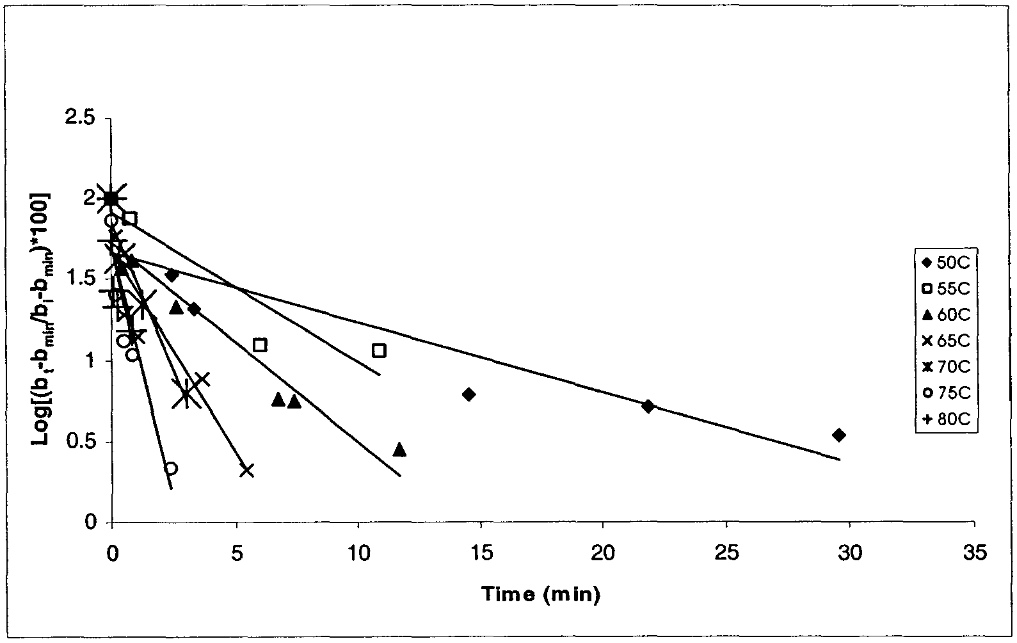


Figure 3.9 Color changes of b* value at the center in fine ham emulsion after time corrected

b*-internal on logarithmic scale vs time on linear scale as affected by thermal treatment at various temperatures. Table 3.4 summarizes the derived kinetic parameters, D value, from these plotted data. D values (logarithmic scale) were then plotted against temperature (on linear scale) and the corresponding z values were likewise obtained as negative reciprocal slopes of log *D* *vs.* temperature (Figure 3.10).

Thermal treatment resulted in a significant increase in the L* value of both internal and surface tissue, most of which occurred during the temperature come-up time. The transient changes in L values of meat emulsions as affected by the thermal treatment nicely fitted log-linear first order model (R^2 = 0.97 and 0.98). The *D* values of L*-internal surface varied from 3.8-83 min with z value at 22°C and D values of L*-surface varied from 1.7-58 min with a z value of 19°C in the temperature range 50 - 80°C. Similar results with a*(internal) and b*(internal) were: D value, 5.7-3.8 min and 1.3 to 24 min and z value, 38°C and 24°C, respectively.

Compared to higher temperatures (≥65°C), samples processed at lower temperatures (50 - 60°C) did not show full development of L* values during the come-up period. The maximum developed value of L* in thermal treatment is 70±1. The L* value on exterior surface reached the maximum development within the first few minutes of thermal treatment (≥65°C). The same phenomenon happened with internal tissue at temperatures ≥70°C. Therefore, to obtain a fully developed L* value within 20 min in the entire tissue, meat-emulsion should be cooked at temperatures ≥70°C, which seems appropriate from microbial

Table 3.4 Kinetic data for different color variables of conventionally processed fine ham emulsion.

Temperature (°C)	D value (min)[1]			
	L* (surface)	L* (Internal)	a* (Internal)	b* (Internal)
50	58.18	82.99	38.37	23.55
55	41.12	61.83	24.22	10.88
60	25.80	19.32	-	8.09
65	8.51	19.38	18.56	3.98
70	6.52	8.69	9.73	2.75
75	2.94	5.65	-	1.57
80	1.70	3.84	5.71	1.31
z	18.70	21.77	37.76	23.67
R^2	0.98	0.97	0.81	0.98

[1] Data for a* (surface) and b* (surface) were not obtained due to *D* value could not be calculated

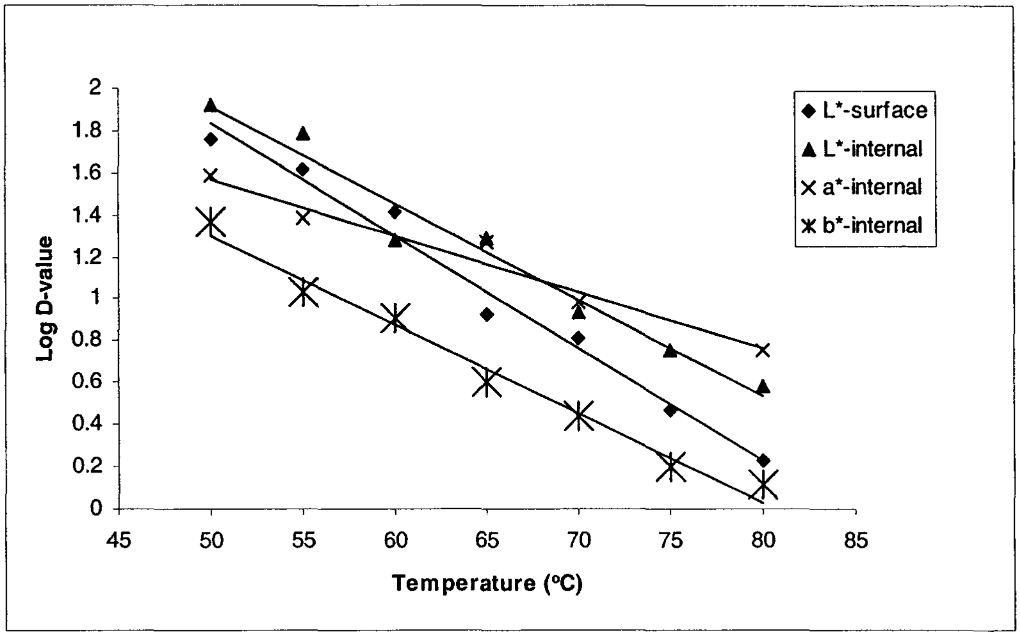


Figure 3.10 Thermal resistance curves of L*, a* and b* color parameters in fine ham emulsion

destruction point of view (safety aspect).

Thermal treatment resulted in sharp increases in internal a*-values. Compared to L*-values, the D values for a* were larger. Again most changes in a* took place during the come-up period. Furthermore, at lower process temperatures (50-60°C), development of a* took place during mostly the holding periods. These results confirmed the first order nature as indicated by their associated high R^2 values (0.81). Increase in process temperature lowered the D values.

Thermal treatment also resulted in a decrease in internal surface b*-values. Compared to L* and a*, the kinetic data for b* were smaller. It is therefore assumed that the thermal treatment affected the color parameter b* the most, even in the lower temperature range (50-60°C). Development of b* values was generally completed within a short heating time (less than the come-up period). The b* value was the least affected parameter of the meat emulsion, still, the destruction curves well fitted the log-linear first order model ($R^2 = 0.98$).

Carballo *et al.* (1996) and Fox *et al.* (1967) reported that process temperature was critical to the color formation in meat emulsion, which was normally processed at 38-76°C. In meat emulsion prepared without added reductant and chopped in air and vacuum-mixed, they reported that color production mainly occurred when temperature reached 50-60°C, and that was no significant change of color at temperature above 60-65°C.

3.4.2.2. Texture

Figures 3.11-3.14 part (a) and Figure 3.15 show texture development (hardness, springiness, gumminess, chewiness, and cohesiveness) in ham emulsions cooked at various temperatures as a function of thermal treatment times. Hardness, gumminess and chewiness increased with an increase of heating time (come-up and holding times) as well as temperature, and a characteristic maximum was reached at a given temperature and heating time. The maximum values were temperature dependent with higher temperatures generally resulting in higher values at shorter heating times. Table 3.5 shows the tabulated values of maximum texture values at each treatment temperature, and the minimum effective time necessary to attain this maximum. In fact, as found with some color parameters, at higher temperatures the maximum value was reached within the come-up period. The cohesiveness and springiness showed a similar results and texture development patterns.

The semi-logarithmic models for the texture values at various temperatures are shown in Figures 3.10-14 part b and their associated kinetic data obtained from regression are presented in Table 3.6 The range of process temperature was from 50-80°C. Thermal treatment caused an increase in the magnitude of all texture parameters, but the rate and pattern of development varied with the attribute, process temperature and holding period. The reaction kinetics again fitted well the log-linear first order model (R^2 = 0.81 to 0.98). The temperature sensitive parameter on texture related D values is illustrated in Figure 3.16. The D value curves were similar to those of color parameters and hence the z values

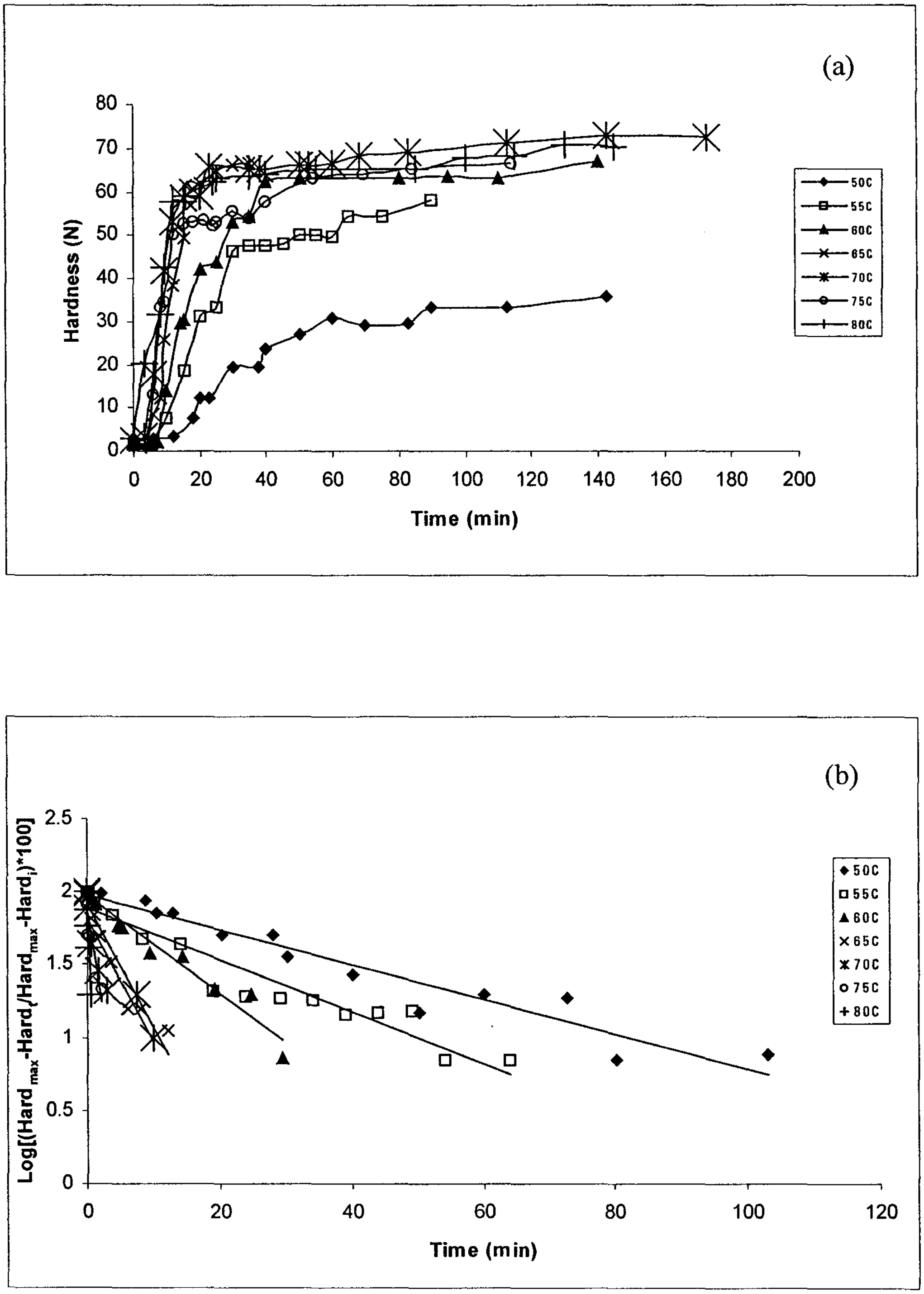
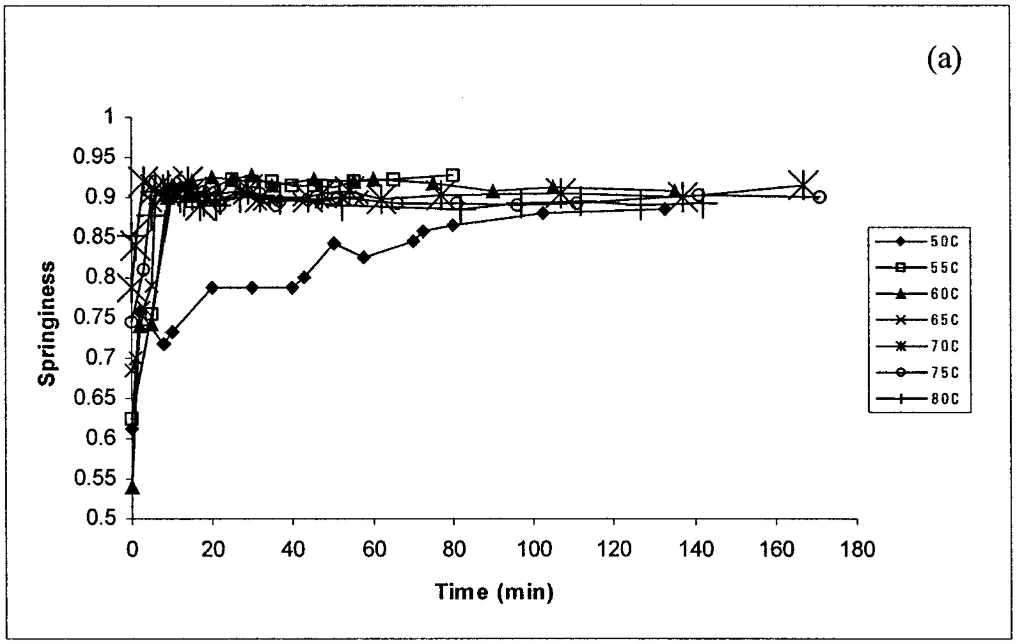


Figure 3.11 Texture changes of hardness in fine ham emulsion (a) uncorrected and (b) corrected heating time; Hard: Hardness



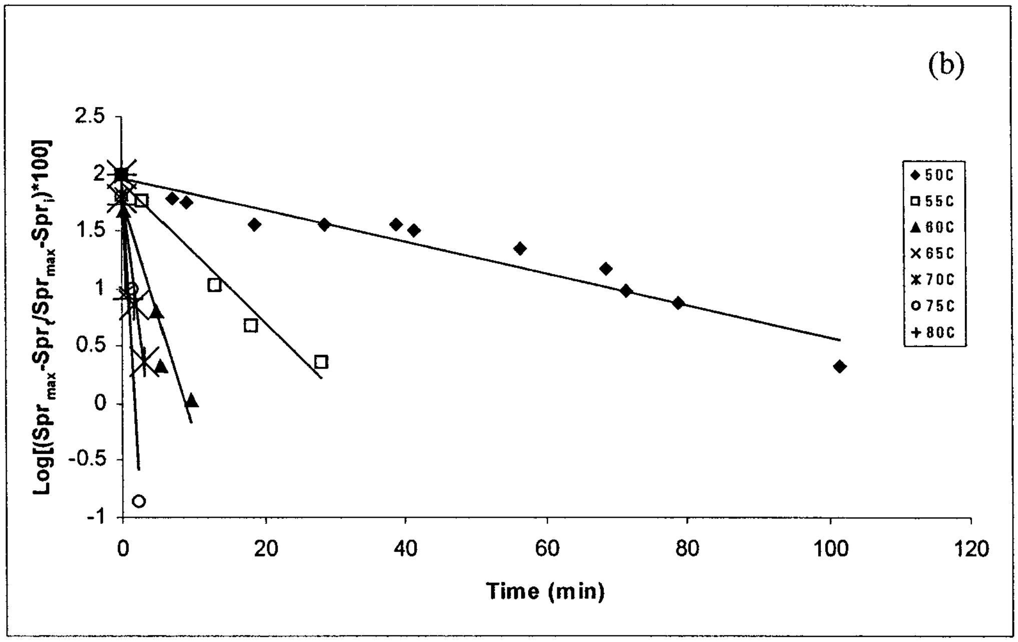


Figure 3.12 Texture changes of springiness in fine ham emulsion
(a) uncorrected and (b) corrected heating time; Spr: Springiness

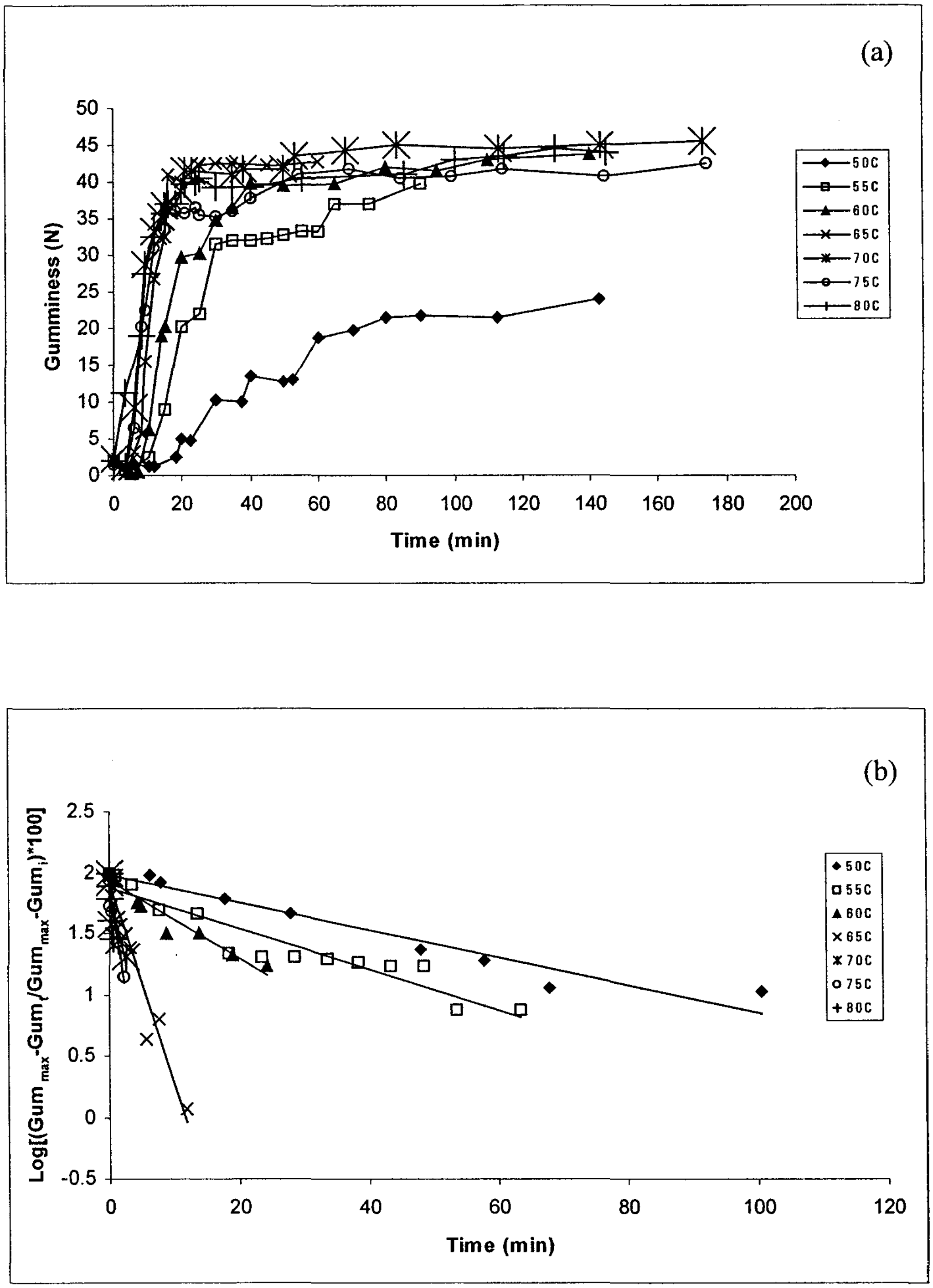


Figure 3.13 Texture changes of gumminess in fine ham emulsion
(a) uncorrected and (b) corrected heating time; Gum: Gumminess

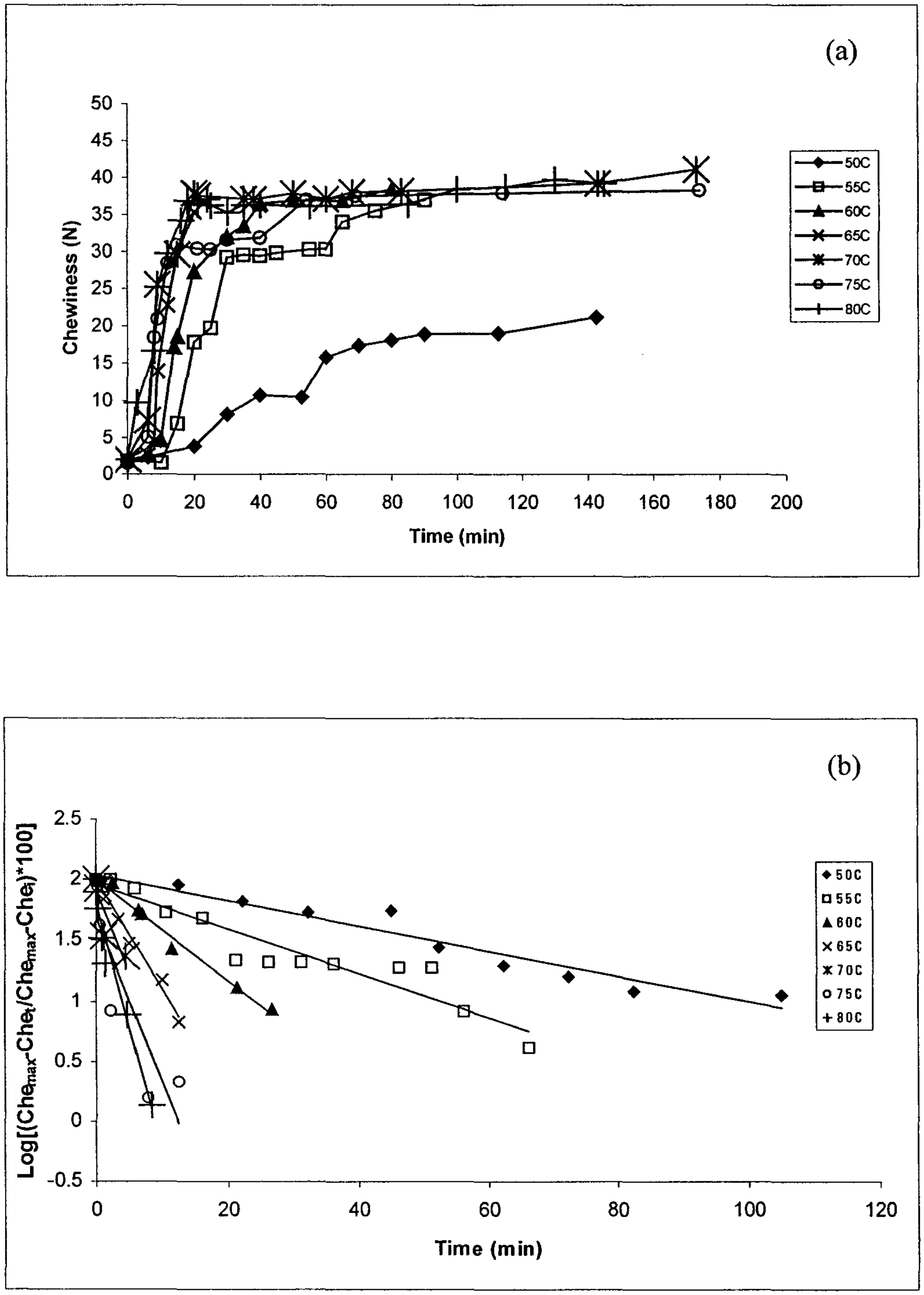


Figure 3.14 Texture changes of chewiness in fine ham emulsion
(a) uncorrected and (b) corrected heating time; Che: Chewiness

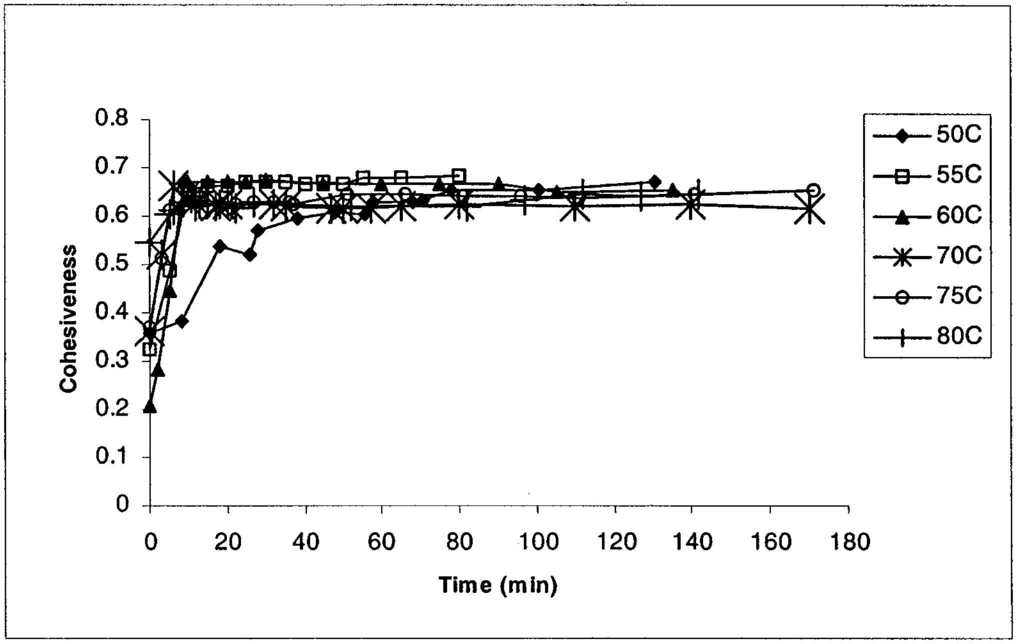


Figure 3.15 Texture changes of cohesiveness in fine ham emulsion uncorrected heating time

Table 3.5 Maximum values of texture profile analysis parameters and the minimum time (t_{min}) taken to reach the maximum under conventional heating of ham emulsions at different temperatures (all values are means of two replicates).

Temperature (°C)	Texture profile analysis parameter									
	HAR_{max} (N)	t_{min} (min)	COH_{min}	t_{max} (min)	SPR_{max}	t_{min} (min)	GUM_{max} (N)	t_{min} (min)	CHW_{max} (N)	t_{min} (min)
50	35.62	142.67	0.67	40.00	0.88	112.67	23.97	142.67	21.21	142.67
55	58.31	90.00	0.67	35.00	0.92	40.00	39.80	90.00	36.93	90.00
60	62.43	50.00	0.67	20.00	0.92	20.00	36.38	35.00	33.46	35.00
65	66.13	30.00	0.65	9.00	-	-	42.24	25.00	38.57	30.00
70	65.82	22.50	-	-	0.92	15.00	36.65	15.00	29.56	15.00
80	65.28	16	0.61	9.00	0.90	12.00	32.51	12.00	29.74	12.00

HAR: Hardness; COH: Cohesiveness; SPR: Springiness; GUM: Gumminess; CHW: Chewiness

Table 3.6 Kinetic data for texture parameters of fine ham emulsion subjected to conventional heating at different processing temperatures.

Temperature (°C)	D-value (min)			
	Hardness	Springiness	Gumminess	Chewiness
50	83.60	72.30	88.69	95.93
55	56.07	16.74	59.24	55.03
60	29.60	4.92	30.83	23.99
65	11.89	-	6.01	11.06
70	11.76	1.98	4.22	7.59
75	3.34	0.92	2.97	7.43
80	1.00	0.70	1.02	4.97
z	16.24	15.82	15.09	22.16
R^2	0.96	0.94	0.97	0.93

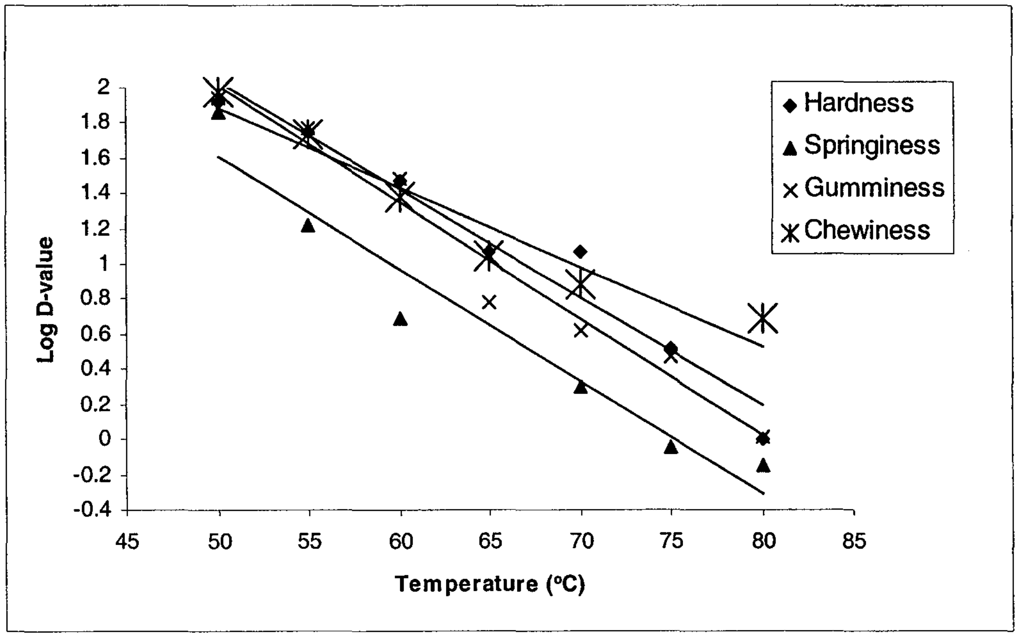


Figure 3.16 Thermal resistance curves of texture parameters in fine ham emulsion

were similarly ranged from 15-22°C.

Hardness of meat emulsions was influenced by processing temperature. Higher processing temperature produced harder meat emulsions. Hardness increased from 35 to 65 N. The meat emulsion formed the firmest gel hardness (65N) at 65°C. Similar increases in hardness have been reported in low-fat sausages (Hunt *et al.*, 1994; Carballo *et al.*, 1996). Cohesiveness and springiness had a similar pattern development by heat treatment. Cohesiveness varied little (0.66 ± 0.01) from 50 – 70°C, but from 75 – 80°C, it decreased to 0.62. Springiness increased from 0.88 to 0.92 between 50 – 55°C, then remained at 0.92 ± 0.01 above 55°C. Hunt *et al.* (1994) found that cohesiveness of low-fat sausages was not affected by internal endpoint cooking temperature at 70 and 80°C. Barbut and Mittal (1990) reported that during cooking of meat emulsions, when internal temperature was over 60°C, there was no appreciable changes in cohesiveness, and changes in springiness were minor.

Heating conditions affected chewiness and gumminess in much the same way as hardness, which was to be expected considering the behaviour of the texture profile parameters (Table 3.5). Chewiness increased from 21 to 38 N mm from 50 – 65°C and dropped slightly to 36 N between 70 – 80°C. Gumminess increased from 24 to 41N from 50 – 70°C and decreased to 36N at 75 and 80°C. Singh *et al.* (1985) reported that ohesiveness, springiness, chewiness and gumminess were all polynomial functions of the final internal cooking temperature and were smaller in the region of 70-75°C.

3.4.2.3. Cooking loss, water holding capacity, and water activity

Figures 3.17–3.19 show changes in cooking loss, water activity and water holding capacity as influenced by the thermal treatment. Table 3.7 and 3.8 tabulates their relative development, characteristic (maximum) values and time to reach these values. Only changes in water holding capacity was consistent enough to further kinetic data analysis.

Cooking losses varied for the different thermal treatment (50-80°C) and holding period (0-180 min). The lowest value 0.63% was observed in the lower thermal treatment (50°C) and the maximum value at 10% at 70°C, which may have been because of fat losses at the higher thermal processed temperature (fat content can affect the water binding property) (Carballo *et al.*, 1996). Mittal *et al.* (1987) determined that the meat emulsion cooking loss ranged from 3.7 to 6.6% and Stech *et al.* (1988) reported slightly higher cooking losses (6.1to 7.3%). The differences may be due to the variation in product composition and cooking schedule (Correia and Mittal, 1991). At a comparable cooking time of 50 min, the cooking losses increased from a low 0.5-1% at 50-55C to 10-12% at 75-80C.

Water holding capacity (WHC) is the ratio of moisture retained in the sample to the initial moisture content, so a higher percentage indicates better binding of moisture in the gel-matrix. The results showed that a maximum WHC of 84% at 50°C and remained around 70% at other temperature (55-80°C). Kinetic study results of WHC showed the *D* value decreased linearly with respect to increasing temperature and fitted well the log-linear first order model (R^2 = 0.94). Hamm (1986) reported that protein changes in frozen meat appeared to

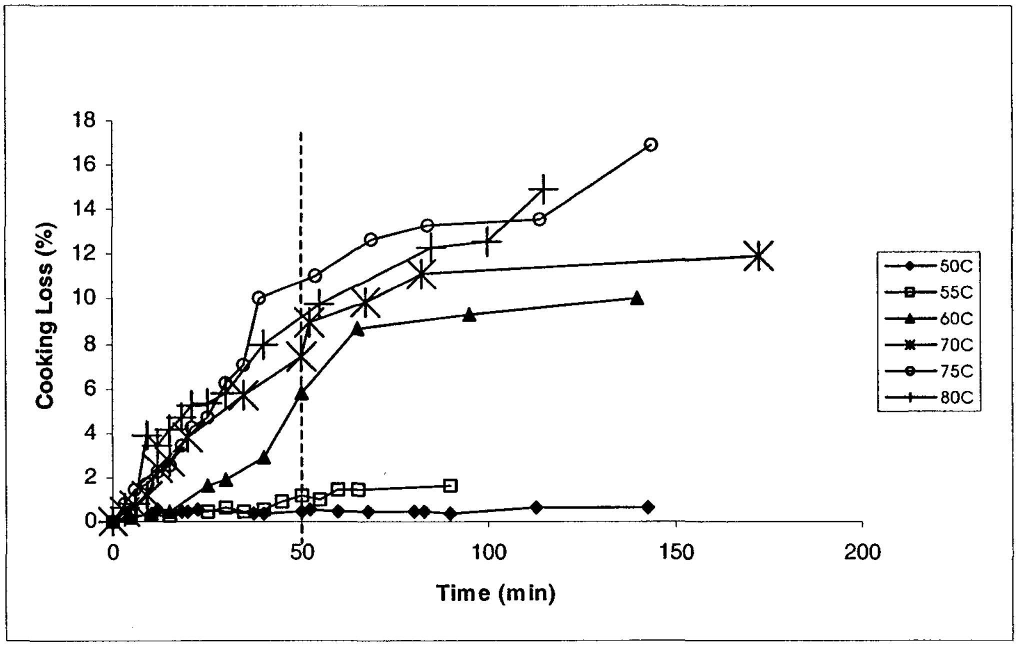
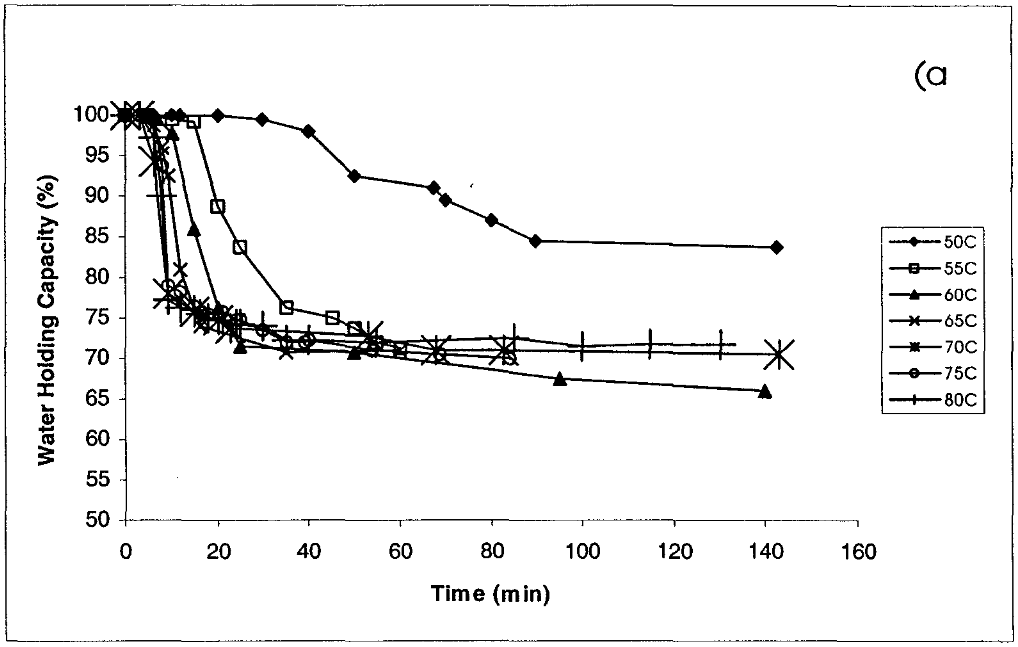


Figure 3.17 Cooking loss changes in fine ham emulsion



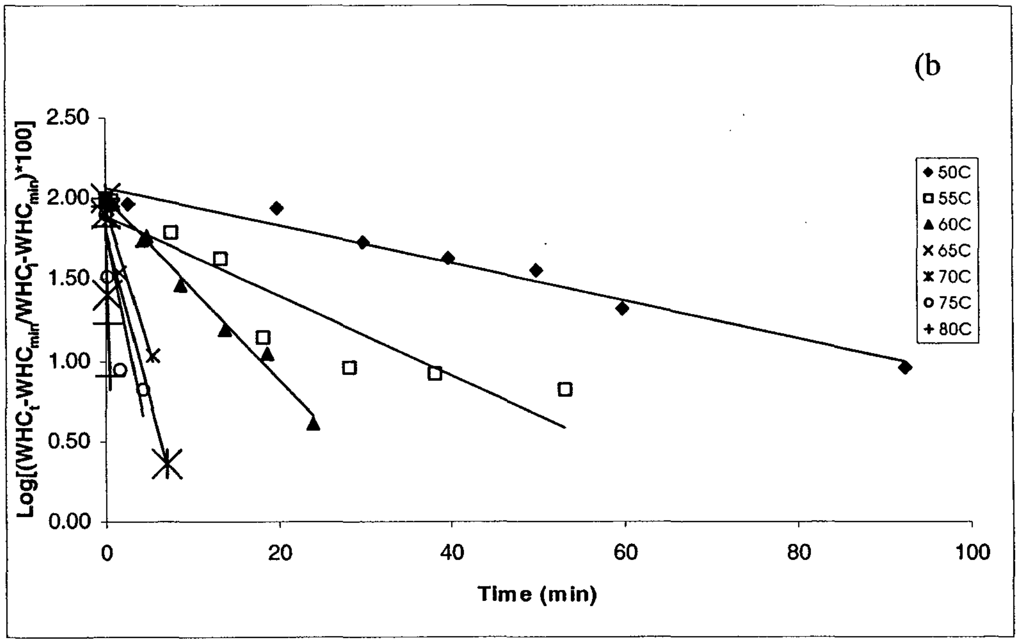


Figure 3.18 Texture changes of water holding capacity in fine ham emulsion (a) uncorrected and (b) corrected heating time

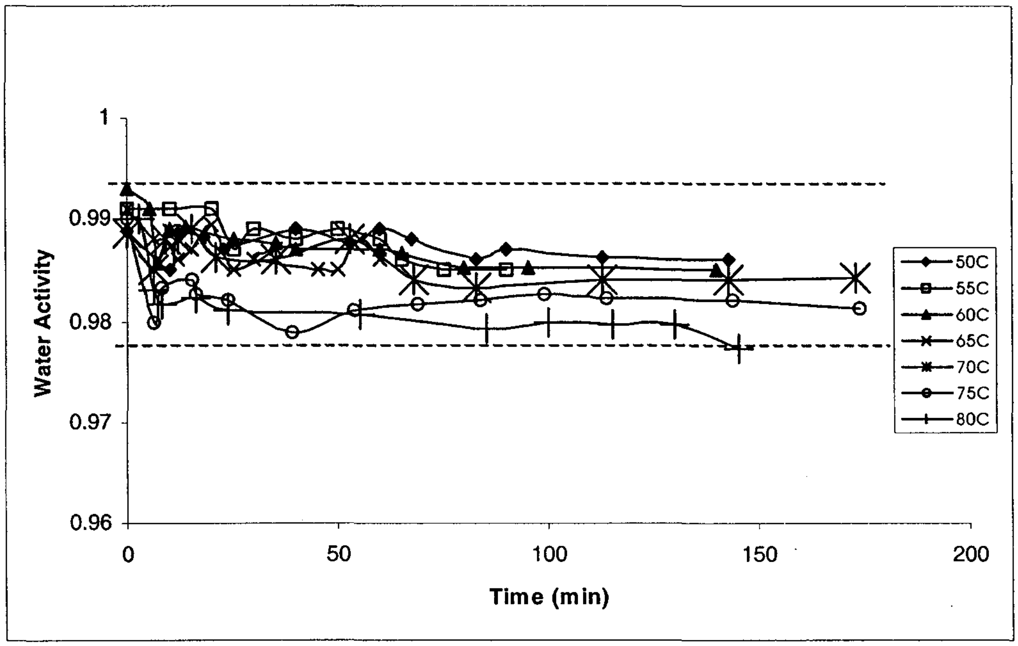


Figure 3.19 Water activity changes in fine ham emulsion

Table 3.7 The cooking loss of fine ham emulsion heated (50 min) at different temperatures

Temperature (°C)	Cooking Loss (%)
50	0.41
55	1.15
60	5.76
70	7.38
75	11.06
80	9.76

Table 3.8 Minimum time required to reach the maximum values of water holding capacity and the D-values under conventional heating of fine ham emulsion at different temperatures

Temperature (°C)	Water Holding Capacity (%)	t_{min} (min)	D value (min)
50	83.70	142.67	87.07
55	73.08	90.00	40.54
60	67.50	35.00	17.76
65	71.07	20.00	5.62
70	70.97	21.00	4.71
75	70.45	18.00	3.53
80	72.24	12.00	0.40
z	-	-	14.40
R^2	-	-	0.94

exert significant influence on WHC after thawing if the meat was stored for longer than one year. In this study, all the meat samples were used for experimentation within 12 months of storage in the freezer at –20°C. The D value curve (Figure 3.20) for WHC was similar to that of other quality parameters with a z value of 14.4°C.

Water activity (a_w) is a critical factor that determines shelf life of food products, and played a significant role with respect to microbial activity (safety and spoilage), the activity of enzymes and affect food quality such as color (Fennema, 1985). Based on food safety aspect, Lee and Styliadis (1996) reported that pathogens were not viable at $a_w \leq 0.85$. In the present experiments, all the a_w results remained at a level of ~0.99 across the temperature range studied. At the a_w level found in the present studies (0.98-0.99), there is no protective effect, and hence the product should be stored at low temperatures to suppress the microbial growth.

3.5. CONCLUSIONS

Changes in the quality attributes (except cooking loss and water activity) of fine ham emulsion during conventional cooking were evaluated and characterized by a first order model. Color and texture development were dependent on both bath temperature and heating time. The water activity remained about the same value through the whole range of thermal treatment under different final temperature. Cooking loss increased with temperature and heating time.

This study provided kinetic data on the effects of thermal treatment on the quality, including color, texture and water holding capacity of ham emulsion. It

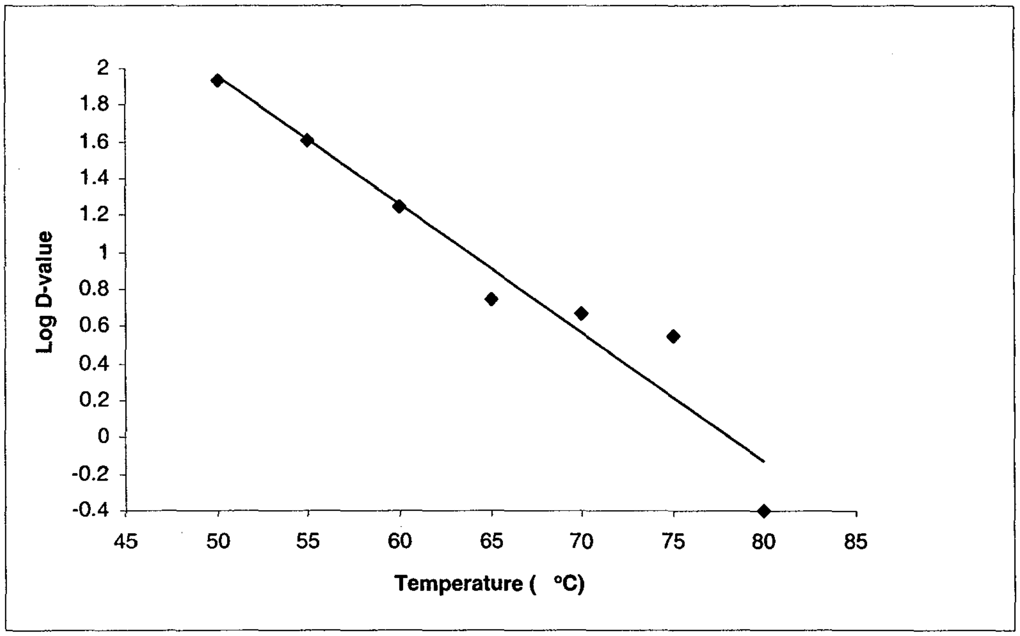


Figure 3.20 Thermal resistance curves of water holding capacity in fine ham emulsion

can serve as a basis for comparing new heating techniques aimed at achieving better quality with shorter heating time and also for comparing the beneficial effects of conventional heating with other heating techniques such as ohmic heating.

CHAPTER 4

STANDARDIZATION OF OHMIC HEATING CONDITIONS

4.1. ABSTRACT

Ohmic heating is resistance heating in which an alternating electric current is passed through a food, when the electrical resistance of the food causes the power to be translated directly into heat. To make quality comparisons with conventionally cooked product, ohmic heating conditions (temperature come-up and hold times) similar to and faster than those employed under conventional heating were required. As ohmic heating depends on product characteristics (size, composition, etc.) as well as system configurations (specifically voltage, in this study), it was necessary to standardize the specific test conditions. The formulation for the ham emulsion was kept the same as used in previous studies (Chapter 3). The applied voltage was sequentially varied and the resulting time and temperature profiles were evaluated. The rate of temperature rise increased with the applied voltage. From the time-temperature-voltage data, it was easy to identify the required voltage necessary to achieve the desired target temperature at an appropriate come-up time. Voltages required were specifically identified to achieve pre-selected come-up times of 5, 10, and 20 min to reach target temperatures of 60, 70, or 80°C. After the target temperature was reached, the test sample was held in the cell to give hold times of 0, 20 and 30 min. Model equations were developed to relate come-up time, temperature and voltage. Electrical conductivity of the ham emulsions was computed from the data and was

similarly modelled. In general, electrical conductivity demonstrated a stronger association with temperature than with the applied voltage.

4.2. INTRODUCTION

Traditional cooking of large-size comminuted meat products in smokehouses takes up to 12 hours. It is energy intensive and results in low production rates. Ohmic heating, a rapid cooking method, offers considerable energy savings and increased production rates which could have interesting applications in the prepared meat industry, especially if the resulting quality parameters are not adversely affected. Little is known about the quality of meat emulsion prepared by ohmic heating especially when prepared under conditions comparable to conventional techniques.

The electrical properties of the material processed, particularly its conductivity, along with the applied voltage and current influence the efficiency of ohmic heating (Alvis and Fryer, 1992). Current and electrical resistance determine the associated energy. Electrical resistance can be lowered by increasing the concentration of salt ions in meat emulsions to be processed (Halden *et al.,* 1990). The electrical conductivity and composition of the product to be processed as well as the heating cell configuration and associated voltage has been reported to influence the ohmic heating rate. However, there are limitations with respect to the current applied and the geometric length of the ohmic static cell. Heating rates are also dependent on the viscosity of solutions due to higher temperature coefficients of electrical conductivity (De Alvis, *et al.,* 1989). Thus, product characteristics such as composition, consistency and electrical conductivity, and system characteristics such as applied voltage level, and test cell configurations etc. will affect the resulting time-temperature profile under ohmic heating conditions.

The specific objective of this study was to identify ohmic heating conditions for achieving pre-set come-up times of 5, 10 and 20 min to reach target temperatures of 60, 70 and 80°C. The 20 min come-time was chosen to represent a heating rate achieved under conventional water bath heating conditions described in Chapter 3 and the other two come-up times were chosen to represent conditions that achieve much superior heating rates than possible under conventional conditions. Two secondary objectives were to model the ohmic heating behavior of meat emulsions within the range of conditions employed in the study, and to evaluate and model the associated electrical conductivity. The formulation was kept identical to the previous study (Chapter 3) to provide meaningful comparisons.

4.3. MATERIALS AND METHODS

4.3.1. Meat Emulsion Preparation

Ham emulsion was prepared (6 kg batches) by using the same method as described in Chapter 3. The prepared emulsion was used on the same day. The ham emulsion was transferred to a hydraulic piston stuffer (J.L. Gourdon Ltée, Montreal, PQ) from the cutting bowl, and filled into four identical ohmic heating cells (same length, diameter, thickness and material, detailed elsewhere). The emulsion temperature was around 10-12°C after these preparations. Test samples were held in a cold room at 10°C, 1) for achieving a uniform initial temperature for all samples, and 2) to minimize deteriorative chemical and other changes. Four ohmic heating test runs were carried out each day and a total of 54 runs were carried out during the study (3 temperatures x 3 come-up times x 3 holding times x 2 replicates).

4.3.2. Ohmic Heating Cell and Cooking

The static ohmic heating cell was made from a Nylon tube (76 mm diameter, 215 mm length Nylon tube with 8.0 mm wall thickness), which would trap a test sample sandwiched between two titanium electrodes (Figure 4.1). The cross-sectional surface area of the electrodes was 4.536×10^3 mm^2 and the gap between them 215 mm. 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 relays and fuses. Six T-Type thermocouples, coated with Teflon to prevent interference with the electrical field, were placed at various positions along the 215 mm length of the Nylon tube (Figure 4.2). Five thermocouples served to measure temperature increments at different locations in the test sample (all located in the lower half of the tube) and one served as an indicator for over-heating. Thermal lags due to the Teflon coating were corrected using data from preliminary calibration experiments where they were calibrated with a certified mercury-in-glass thermometer (National Research Council NRC #1598, Canada) and uncoated thermocouples. These tests were carried out under conventional heating conditions in a well-agitated

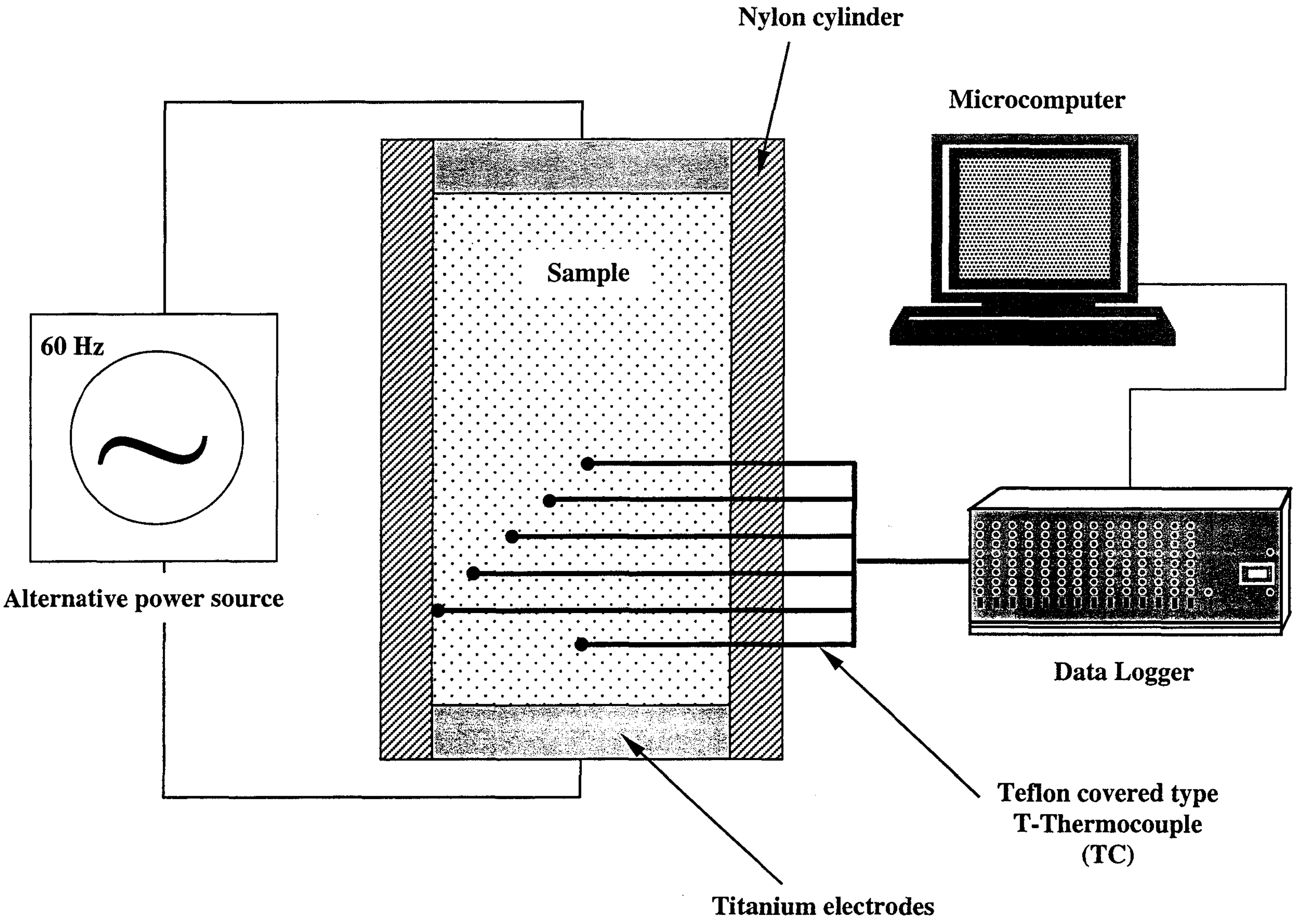


Figure 4.1 Schematic of the static ohmic heating cell

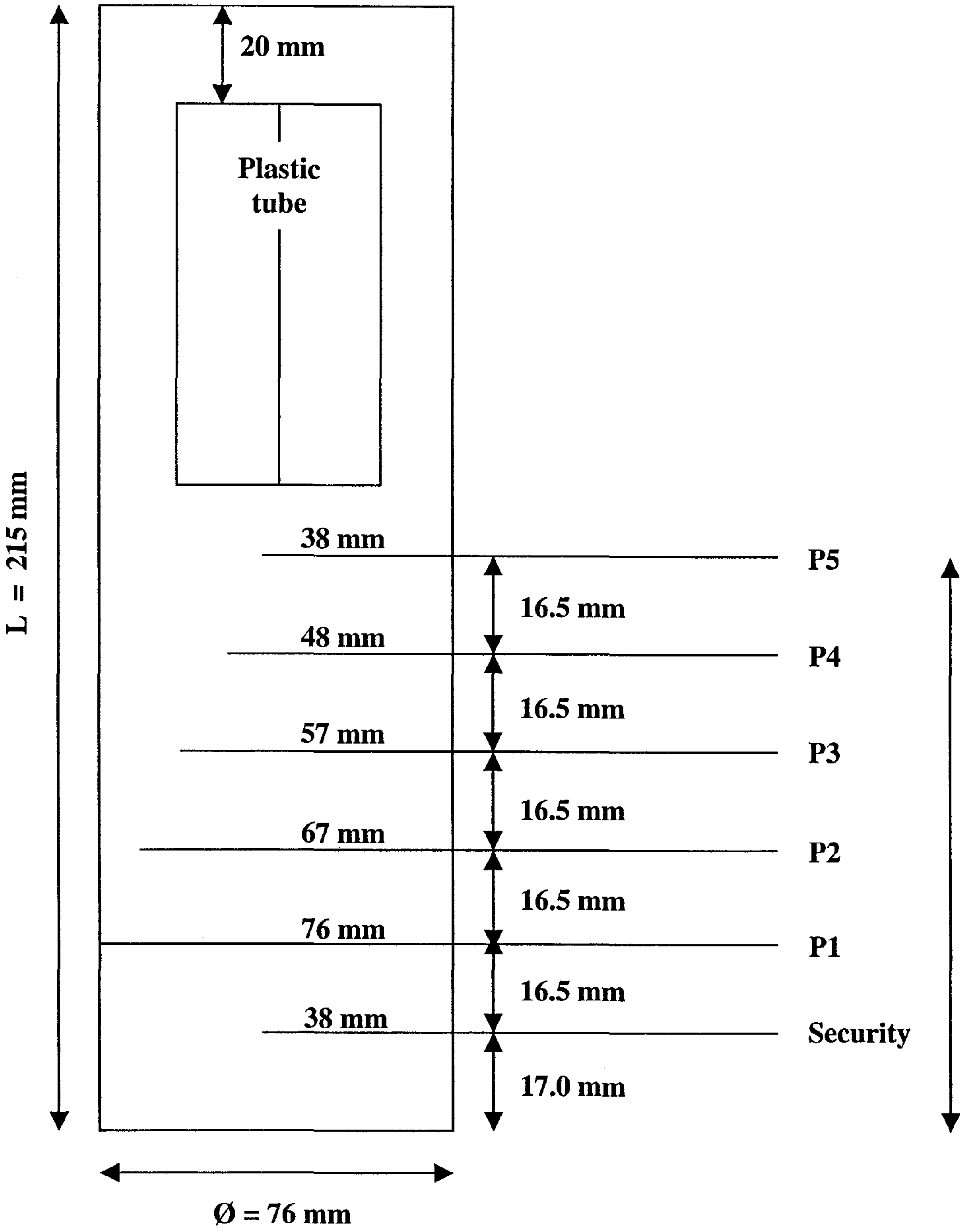


Figure 4.2 Schematic of the location of thermocouple within static ohmic heating cell

temperature-controlled water bath, over a temperature range, 0 to 100°C. A pressure sensor (Omega, Stamford, CT) was installed on the top end of the ohmic cell, to avoid over-pressurization during ohmic heating. In each ohmic heating experiment, a test sample containing roughly 1.0 kg of fine ham emulsion was introduced into the Nylon cylinder. In order to obtain the uniform size and shape of ohmic heating ham product as the conventional heating, an open ended plastic tube (diameter, 25.4 mm, and length, 75 mm) was inserted from the upper end of the test chamber, along the central axis and located approximately 20 mm below the upper electrode. The tube was removed after the test and the sample held within the tube was used for quality measurements in a manner similar to those cooked under conventional heating conditions (Chapter 3). The purpose of this tube was to trap an appropriate size sample for quality measurements following the heating without disturbing the sample. The test sample was heated from 12°C to 60, 70 or 80°C using different (constant) voltages between 40 and 100 V. During the experiment, time (limited to a maximum of 3 h), temperature, voltage and current data were recorded at selected intervals using a data logger (Fluke Hydra Bucket, Fluke Corporation, Everett, WA) connected to a computer. Voltage and current were used to calculate the electrical conductivity, σ (*S/m*):

$$\sigma = 100\left[\left(\frac{1}{R}\frac{L}{A}\right)\right] \tag{4.1}$$

where:

R was the resistance of the material (*ohm*), determined as measured voltage (*V*) divided by measured current (*I*),

$$R = \frac{V}{I} \qquad [4.2]$$

L was the gap between electrodes (*cm*), and

A was the cross-sectional surface area of the electrodes (cm^2).

The power input, W, supplied to the fine ham emulsion sample (W) was:

$$W = I^2 R \qquad [4.3]$$

4.4. RESULTS AND DISCUSSION

4.4.1. Ohmic Heating Behavior of Ham Emulsions

Figure 4.3 shows typical time temperature profiles of ham emulsions heated using the static ohmic heater as related to the applied voltage. Each curve represents the heating profile at a given voltage. As the applied voltage increased, the sample temperature increased more rapidly thereby reducing the come-up time for any specified temperature. From this figure, the come-up time required to achieve various target temperatures was evaluated. Figure 4.4 shows the relationship between applied voltage and come-up time of fine ham emulsion to reach the target temperatures of 60, 70 and 80°C. These are combined in the form of a response surface plot in Figure 4.5 showing come-up time vs temperature and voltage clearly demonstrating that come-up time decreased as the voltage increased. As can be expected a longer come-up time was required to reach a higher temperature (at a given voltage). The computed voltage to be applied under ohmic processing to obtain specific come-up times of 5, 10 and 20 min for 60, 70 and 80°C is shown in Table 4.1. The developed model relating come-up time (CUT) to voltage (V) and temperature (T) (from which the response surface

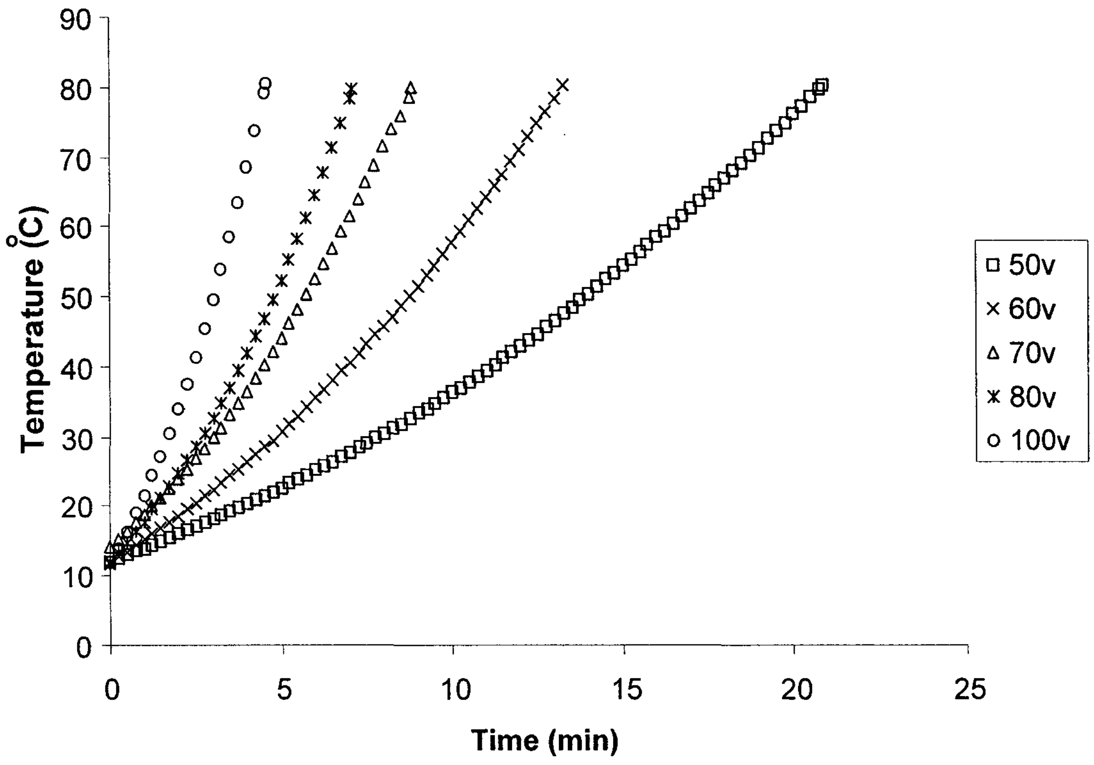


Figure 4.3 Typical time temperature profiles under ohmic heating conditions

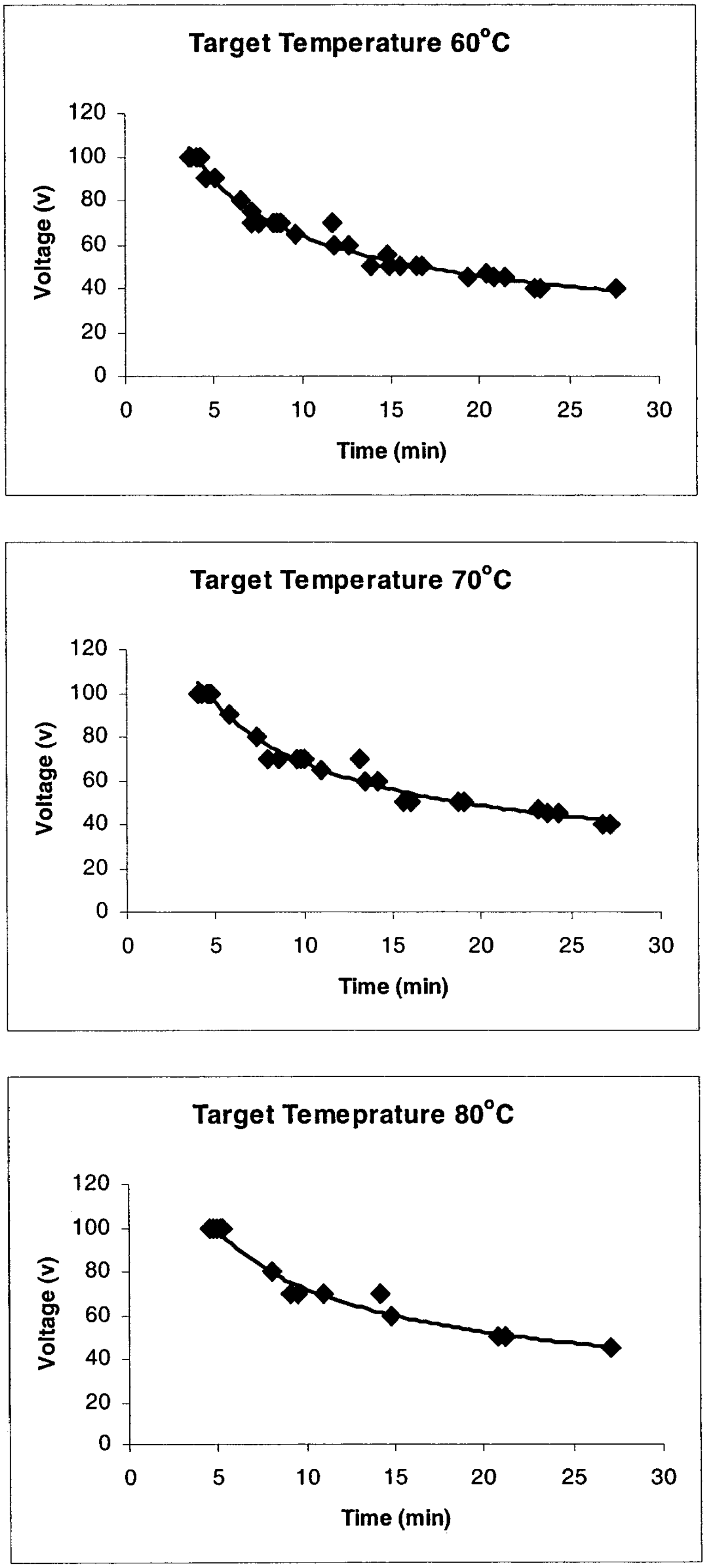


Figure 4.4 Voltage versus come-up time curves under ohmic heating of ham emulsions

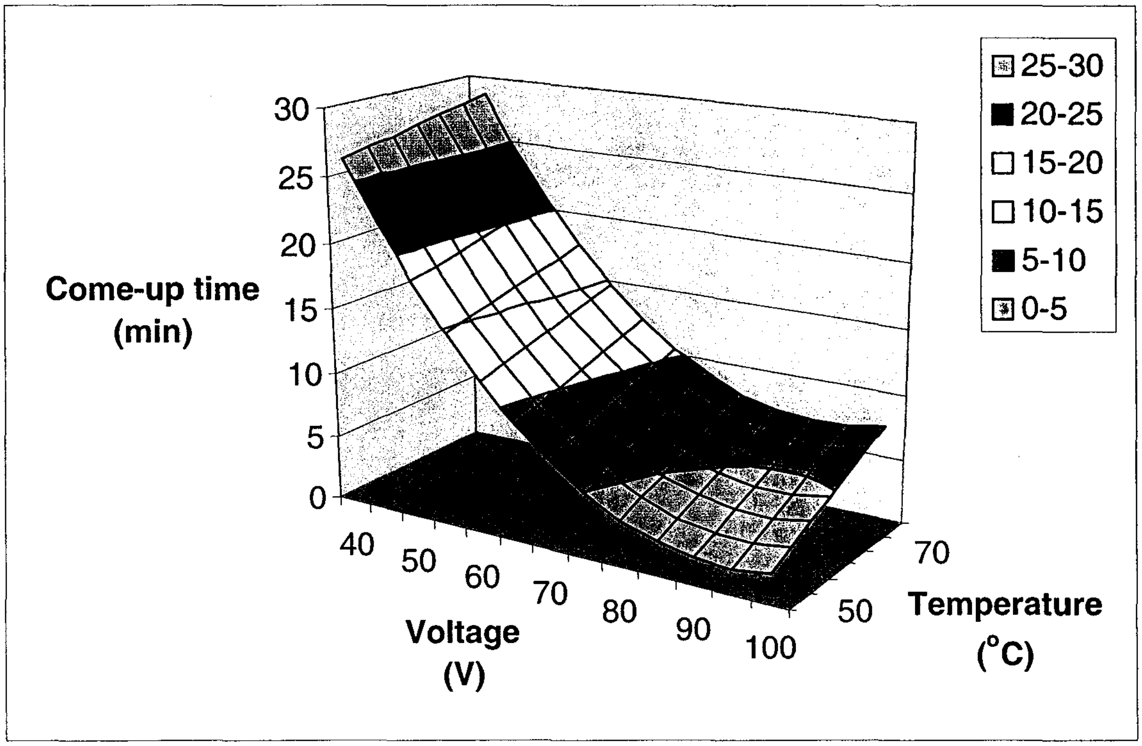


Figure 4.5 Effect of voltage and temperature on come-up

Table 4.1 Estimated voltage requirement for achieving selected CUT (5-20 min) at different temperature (60-80 °C)

Temperature (°C)	CUT (min)	Voltage (v)
60	5	90
	10	64
	20	46
70	5	95
	10	68
	20	48
80	5	99
	10	72
	20	52

plot was generated) is shown below.

$$CUT = 76.582 - 1.678V + 0.008V^2 + 0.002VT \qquad R^2 = 0.9593 \qquad [4.4]$$

Figure 4.6 shows the heating rate obtained under the established ohmic processing conditions. The heating rate somewhat linearly increased with applied voltage. The temperature profiles at different locations within the static cell during ohmic heating under different conditions are shown in Figure 4.7. In each test run, the thermocouple located along on the wall near the end of the cell (P1, Figure 4.2) presented the lowest temperature and that situated near the centre (P5), the highest. Temperatures measured at P1 and P2 were lower due to the heat loss across the wall of the static cell, resulting in the product being undercooked in this region. Thermocouples P3, P4 and P5 were placed near the central locations showed somewhat similar temperature profiles. Hence, for subsequent studies to evaluate the effect of ohmic heating on quality of cooked ham-emulsions (Chapter 5), samples were recovered from these regions. It should be noted that the plastic tube is positioned in the upper half of the ohmic heating unit in the central region, about 20 mm below the electrode, and, by symmetry, the samples placed in this region can be considered to heat uniformly.

4.4.2. Electrical Conductivity of Ham Emulsions

Electrical conductivity, electrical resistance and power absorption of ham-emulsions under the ohmic cooking conditions used in this study were computed from Equations 4.1-4.3. As before, these were modelled to relate them to temperature and voltage. The response surface plots of electrical conductivity,

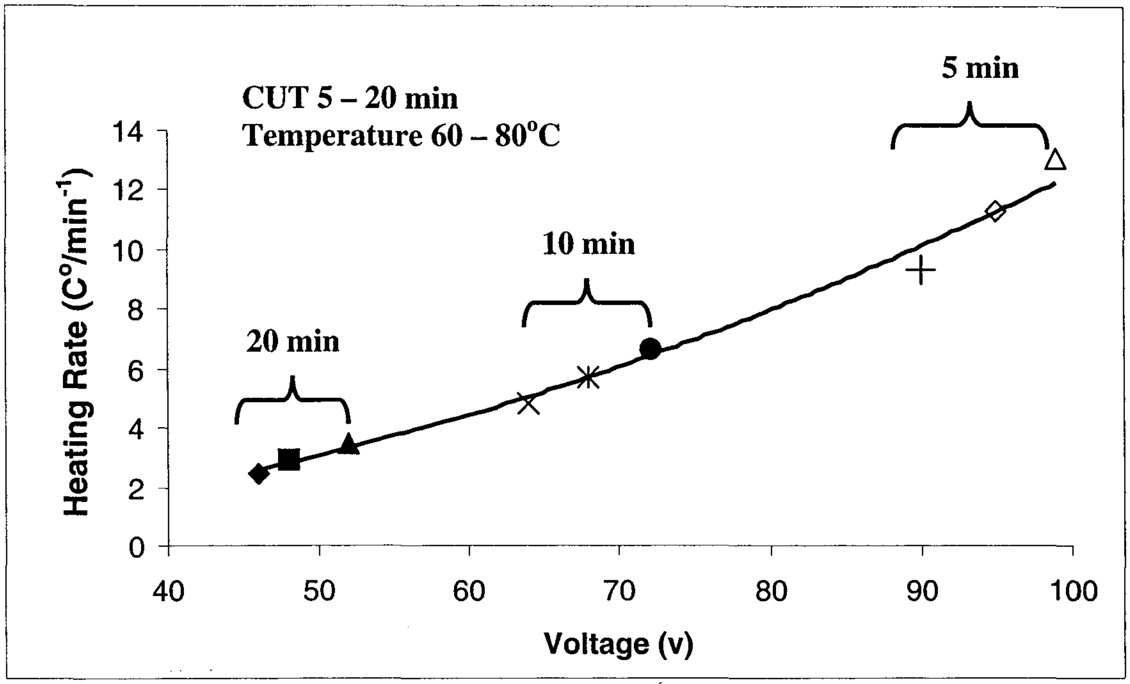


Figure 4.6 Temperature profile under the established ohmic heating conditions

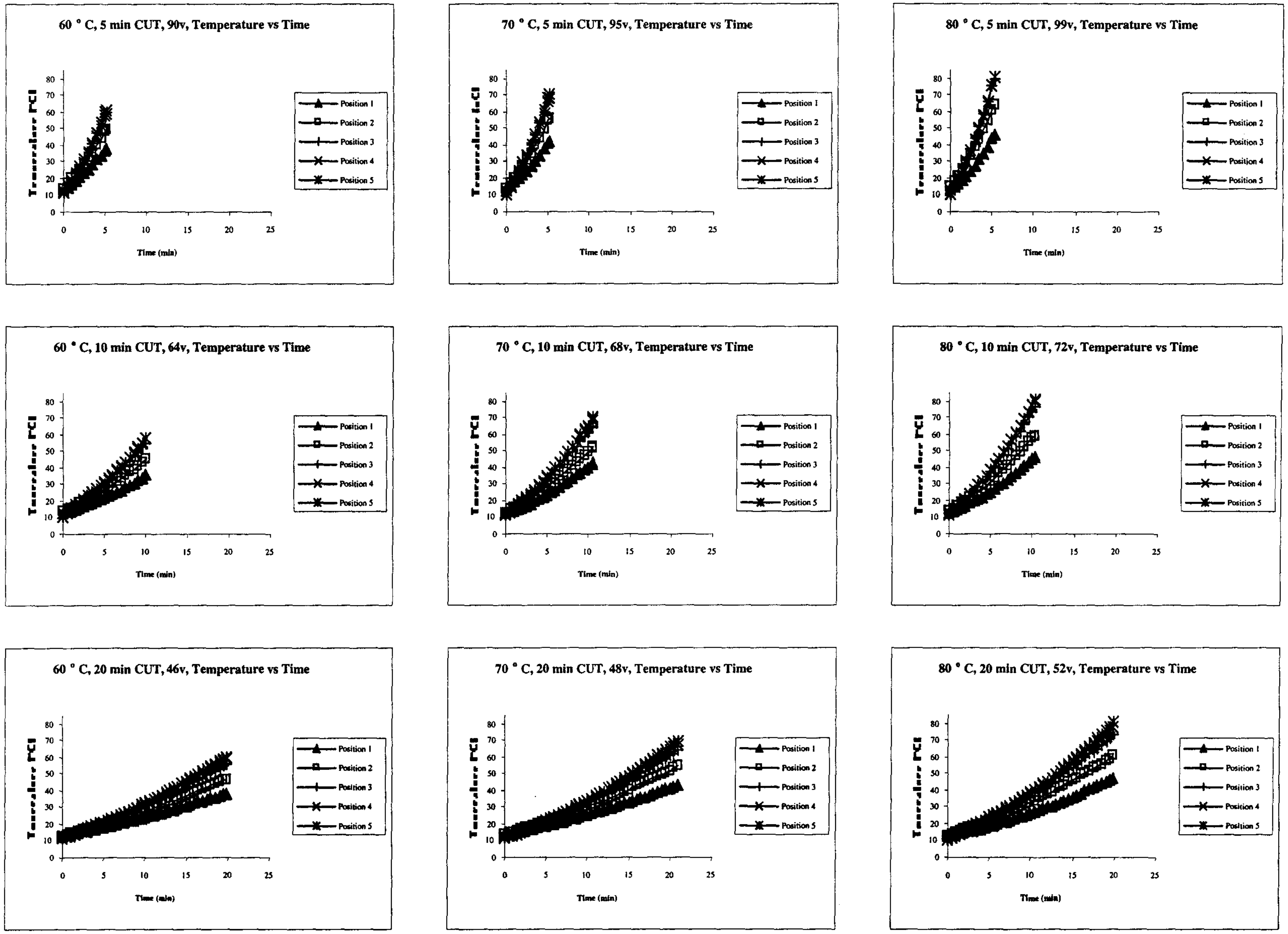


Figure 4.7 Temperature profile at different location within the Ohmic static cell during ohmic heating of ham emulsions

electrical resistance and power absorbed are shown as response surface plots in Figures 4.8-4.10. Electrical conductivity of ham emulsions increased with an increase in temperature or voltage (Figure 4.8). The rate of decrease with respect to temperature was much more than with voltage in the range study. Since the electrical conductivity is inversely related to the resistance, the electrical resistance decreased with an increase in temperature or voltage (Figure 4.9). Again the rate of decrease was more pronounced with temperature than with voltage. Earlier studies on electrical conductivity have also reported conductivity to increase linearly with temperature in all cases (Fryer *et al.,* 1993; Marcotte *et al.*, 1998b).

Fryer *et al.* (1993) expressed the linear relationship between electrical conductivity and temperature for high viscosity solution differently as:

$$\sigma = \sigma_0 + K_T(T) \qquad [4.5]$$

where T is in °C and σ_0 at 0°C is in S/m. K_T is in S/m°C. But, results of reference electrical conductivity are usually not reported at 0°C. Electrical power absorbed also increased with temperature or voltage (Figure 4.10). The trend described is a bit curve-linear with respect both temperature and voltage effects. The voltage effect in this case appears to dominate over the temperature effect. The model equations developed for conductivity, resistance, and power absorption are shown below

Conductivity (*C*):

$$C = 2.247 + 0.047T - 0.009V + 6.549\times10^{-5}V^2 + 0.0002TV \quad R^2 = 0.9990 \quad [4.6]$$

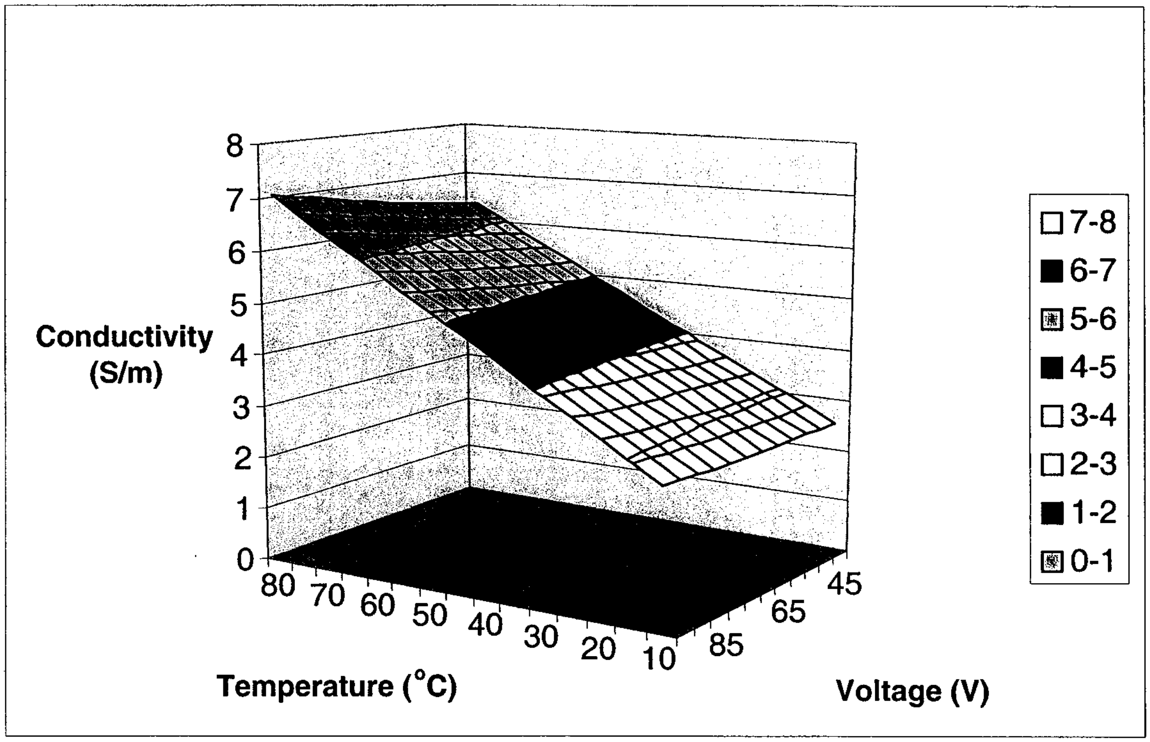


Figure 4.8 Effect on temperature and voltage on electrical conductivity

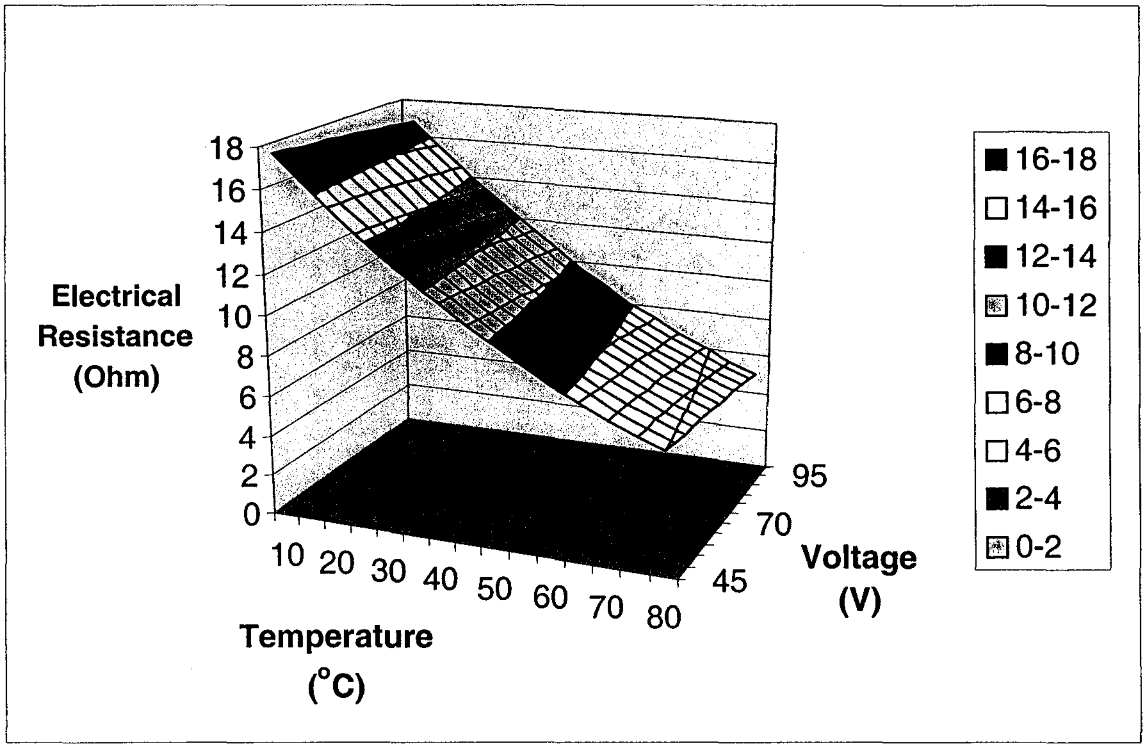


Figure 4.9 Effect on temperature and voltage on electrical resistance

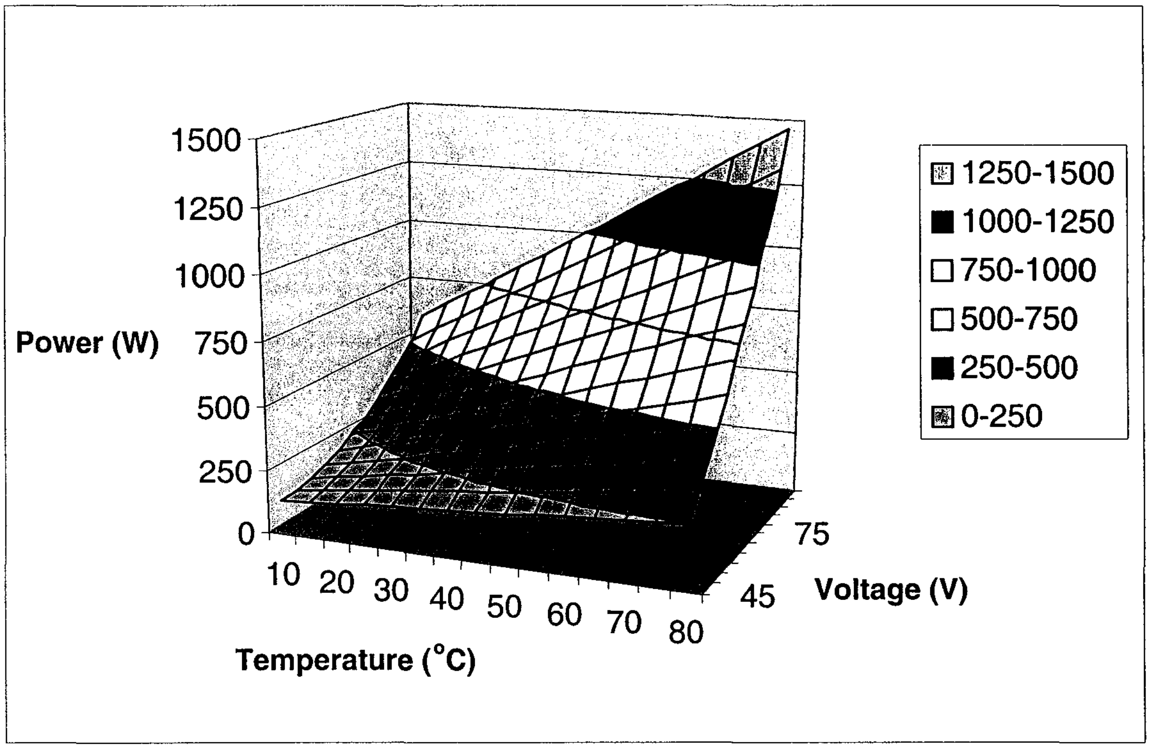


Figure 4.10 Effect on temperature and voltage on nominal power

Resistance (R):

$$R = 20.460 - 0.258T + 0.001T^2 + 0.00012V^2 \qquad R^2 = 0.9960 \quad [4.7]$$

Power (P):

$$P = 442.371 - 7.423T - 13.091V + 0.133V^2 + 0.200TV \qquad R^2 = 0.9986 \quad [4.8]$$

where T= temperature and V = voltage.

4.5. CONCLUSIONS

The ohmic heating profiles of fine ham emulsion were gathered to standardize the ohmic heating conditions for subsequent studies. It was observed that the heating behavior was influenced by temperature, applied voltage and come-up time. Heating was more rapid at higher voltages. The heating rate increased almost linearly with the applied voltage. In all cases, heating was found to be fairly uniform along the central region both in the radial and longitudinal directions. Test samples for further studies were place in this region.

Under constant voltage applied to the fine ham emulsion, electrical conductivity and absorbed power increased with temperature and voltage. An opposite trend was observed for electrical resistance. Electrical conductivity and electrical resistance demonstrated a stronger association with temperature than with the applied voltage while the absorbed power was much more influenced by the voltage.

CHAPTER 5

QUALITY COMPARISONS OF HAM EMULSIONS COOKED UNDER OHMIC AND CONVENTIONAL HEATING CONDITIONS

5.1. ABSTRACT

This phase of study was conducted to compare the quality changes in fine ham emulsion subjected to ohmic heating under different rates, and to compare them with those subjected to similar treatments under conventional heating conditions. Fine ham emulsions were prepared according to a standard specification and subjected to previously established ohmic heating conditions to achieve three selected come-up times (5, 10, and 20 min) and three different holding times (0, 20 and 30 min) at three cooking temperatures 60, 70 and 80°C (each separate run). Test samples were also prepared under comparable conventional heating conditions (but only with a 20 min come-up time). Cooked samples were evaluated for various quality parameters (color, texture, cooking loss, water holding capacity and water activity). Cooking temperature and come-up time significantly ($p<0.05$) influenced the color and texture of test samples subjected to ohmic heating conditions, higher temperatures, shorter come-up times and longer holding times showing lighter color, and softer texture. Furthermore, compared to the conventionally cooked product, ham emulsions cooked under ohmic heating conditions were lighter and had more "pink or red" color, softer and chewier texture ($p<0.05$). The associated water holding capacity and cooking loss were also lower ($p<0.05$) in ohmic heated samples than in the

conventionally cooked samples. These results show that the rapid heating achieved under ohmic heating conditions provide some improvements in product quality in comparison to the conventional heating method. In addition, cooking time can be reduced by 75% even for much larger samples which could result in better production rate.

5.2. INTRODUCTION

The acceptance or rejection of a food product is conditioned by sensory stimuli. Product color and texture are external quality attributes on which product acceptance or rejection decisions are based. The major challenge of the food industry, therefore, is to provide food products that, in addition to being safe, have an attractive color and acceptable texture. The traditional cooking of comminuted meat products in large scale is smoke houses which can take up to 12 hours due to the slow rate of heat transfer associated with these processes. This long period of cooking can affect the product quality, especially color, texture and nutritive value.

Ohmic heating is a direct heating method in which alternating electrical current is passed through an electrically conducting food product (Biss et al., 1989). Heat is internally generated, resulting in a rapid heating rate. Since heat is simultaneously generated in liquid and solid phases, the temperature increase in the product is uniform, compared to the conventional process in which heat is applied at the external boundary (de Alwis and fryer, 1990, Parrot, 1992). The major benefit of the process is that the heating takes place volumetrically and the product does not experience a large temperature gradient within itself as it heats. In principle, the heating effect is similar to that obtained with microwaves, where electric energy is transformed into thermal energy uniformly throughout a food. However, the major advantage of ohmic heating compared to microwave heating is that the depth of penetration is not limited, and the extent of heating is determined by electrical conductivity throughout the product and the residence time in the electric field. Several researchers (Palaniappan & Sastry, 1991b, Parrott, 1992, Reznick, 1996, Kim *et al.*, 1996a, Lima *et al.*, 1999) have studied the effect of ohmic heating on the quality of different types liquid, solid and solid - liquid food products potentially demonstrating the advantages of ohmic heating over the conventional methods. However, there is only limited data published on fish protein emulsions. Yongsawatdigul *et al.* (1995a and b) reported that surimi gels prepared by ohmic heating showed more than twofold increase in shear stress and shear strain over conventionally heated gels. Park *et al.* (1998) also reported that pacific whiting gels rapidly heated by ohmic heating demonstrated superior shear stress and shear strain, and degradation of the myosin and actin was significantly minimized.

The objective of this phase of study was to compare the quality changes of fine ham emulsion subjected to ohmic heating under different rates (come-up periods), and to compare them with conventional heating treatments (20 min come-up time) with different holding periods (0, 20 and 30 min).

5.3. MATERIALS AND METHODS

5.3.1. Emulsion Preparation and Heating Conditions:

Fine meat emulsion was prepared as detailed in Chapter 3. For ohmic heating, about one kg fine meat emulsion sample was filled in to the static ohmic heating cell and subjected to pre-selected ohmic heating conditions as detailed in Chapter 4 (Table 4.1). This yielded ohmically heated samples with 5, 10 and 20 min come-up time 0, 20 and 30 min holding time at cooking temperatures of 60, 70 and 80°C with. For conventional heating, test samples filled in to cylindrical tubes (size diameter = 25 mm; L = 75 mm) and subjected to conventional heat treatment as detailed in Chapter 3 (come-up time 20 min, holding times 0, 20 and 30 min at 60, 70 and 80°C). As detailed in Chapter 4, for quality evaluation purposes, only the test sample placed within the plastic tube (size diameter = 25 mm; L = 75 mm) introduced in the upper central region below the electrode was used. This procedure allowed the recovery of ohmic heated test samples with minimal disturbance to permit quality comparisons between samples subjected to various ohmic and conventional heat treatments. Immediately after heat treatment, test samples were cooled and stored in a refrigerator at 4°C and quality parameters were evaluated next day as detailed below and were statistically compared.

5.3.2. Quality Measurement and Data Analysis

Color, texture, cooking loss, water holding capacity and water activity were evaluated as detailed in Chapter 3. Test samples from conventional heating conditions were removed from the cylindrical holders for quality evaluation.

5.3.3. Statistical Analysis

The SAS computer program (SAS Institute Inc. 1997) was used to study the individual and interaction effects of influencing factors (processing treatment, temperature, come-up time, and holding time). Using the same statistical program, least-significant-difference (LSD) grouping tests were performed to see if there were statistically significant differences among the means of the various variable levels under investigation.

5.4. RESULTS AND DISCUSSION

5.4.1. Ohmic Heating

5.4.1.1. Heating behavior

Figure 5.1 shows typical time-temperature profiles of test samples during the ohmic heating indicating a slightly concave upwards come-up curve. Relative to conventional heating observed (Chapter 3), however, time-temperature profiles under ohmic heating conditions could almost be considered linear. ohmic heating at different voltages were required to achieve different temperatures with a specific come-up periods or to achieve different come-up times at a given temperature. Hence different combinations of ohmic heating conditions were used to get the desired effect (different come-up times and different temperatures). During the holding time, the sample temperature was kept study by intermittent on/off of the ohmic heating system. Since the Teflon test cell used in

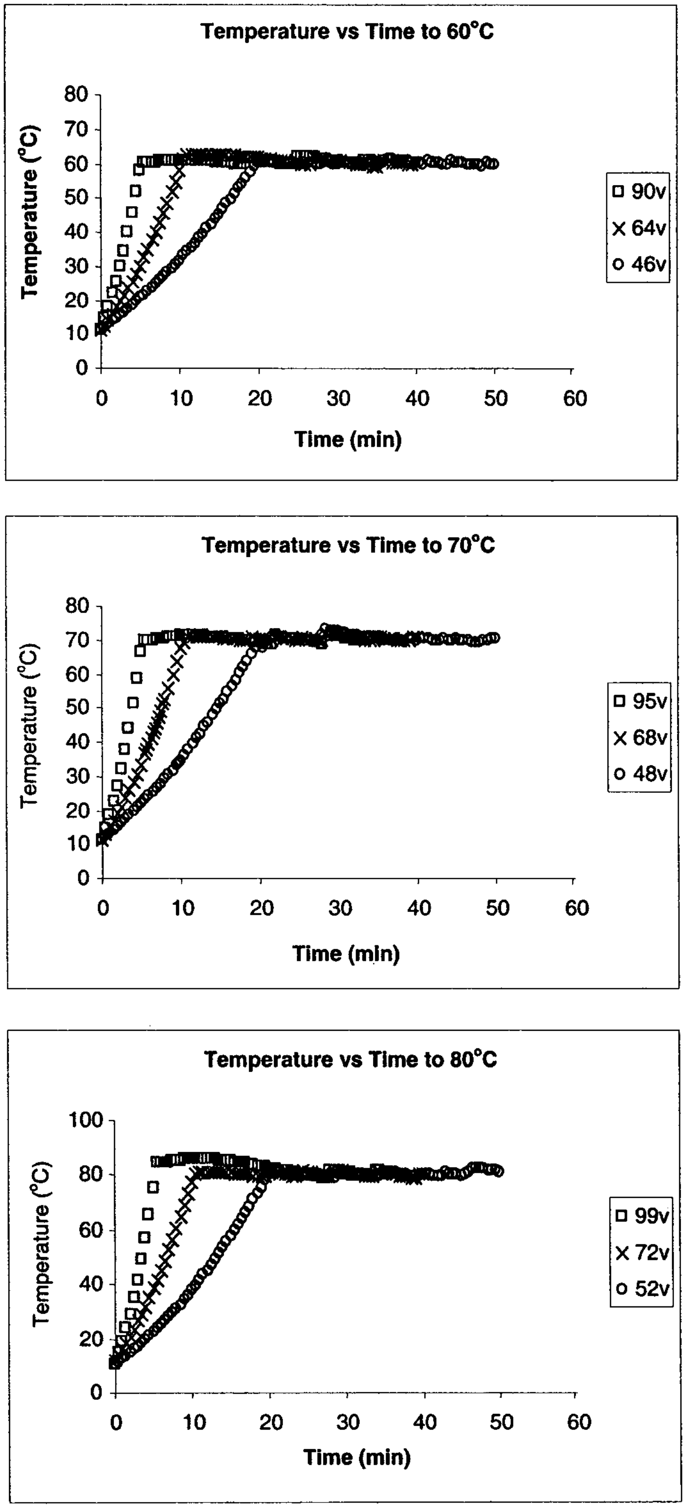


Figure 5.1 Temperature profile under different come-up time

the study provides some insulation effect to prevent quick temperature drop, the heat input during the holding time was minimal (intermittent heating for 20-30 s would keep the temperature steady for about 5 min). The average temperature was maintained ±1°C.

5.4.1.2. Color changes

Figures 5.2 to 5.7 show the tristimulus L*, a* and b* values at the cut surface (designated as Center or Internal) and the cylindrical outer surface (designated as Surface) of test samples subjected to ohmic heating under various test conditions. The mean effects and significance of interactions are presented in Table 5.1 and 5.2, respectively. Test results indicated that the color parameters, L*, a* and b* values (except with surface a*-value) were generally influenced the process parameters - temperature, come-up period and holding time. Analysis of variance results (Table 5.2) indicated all test factors, except surface cut a*-value, and their interactions to be statistically significant ($p<0.05$). Higher temperatures resulted in slightly "lighter" colors as evidenced by the higher L* values. Koutchma *et al.* (2000) also observed similar results with thin-profile ham emulsions prepared under conventional heating conditions. The surface L* values were also marginally higher than the internal L* values, possibly due to small temperature variations from surface to center. Shorter the come-up times had again slightly higher L* values. The longer holding time effect was somewhat mixed, with the 20 min holding giving slightly larger L* values.

The a* values (redness) of all the ohmic processed product were higher than

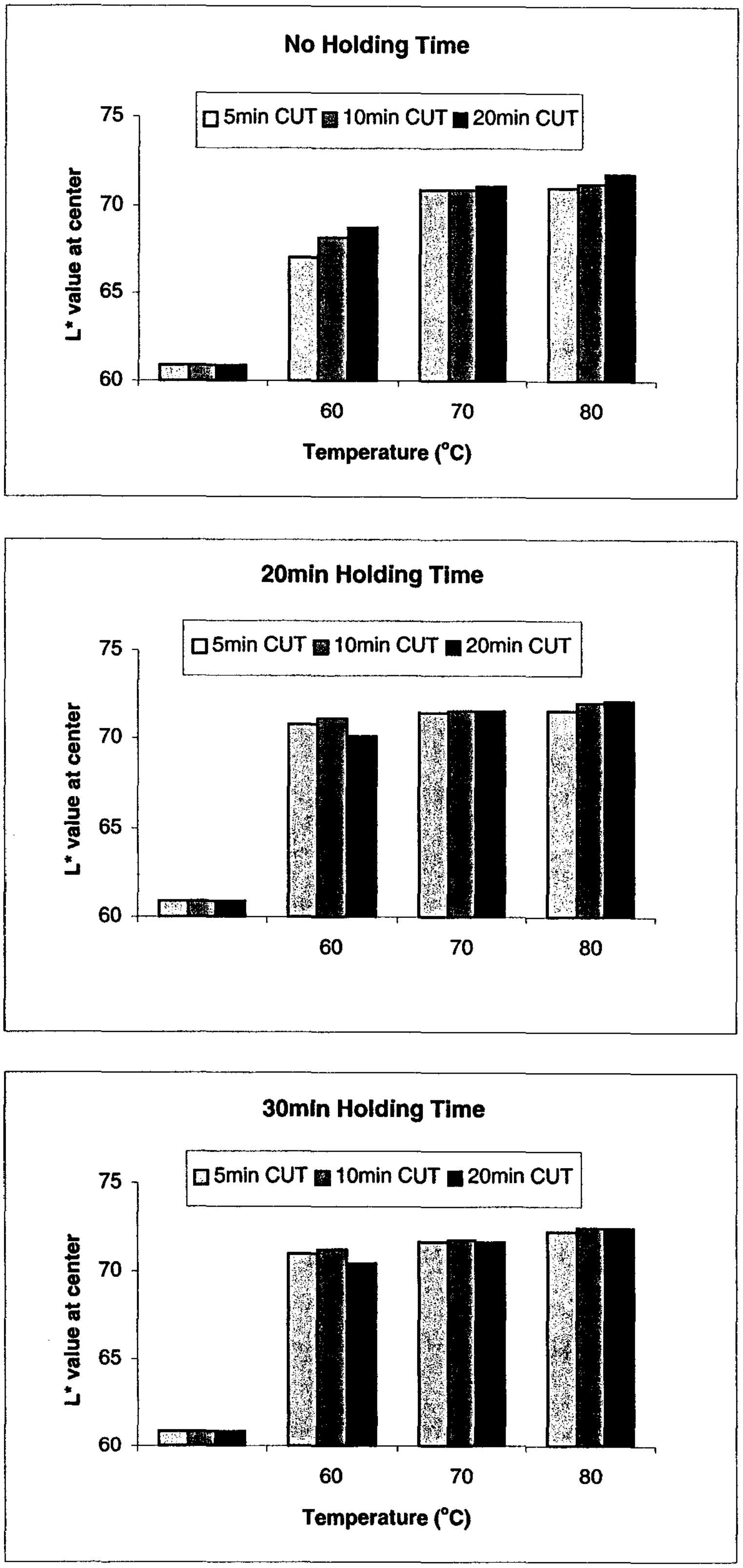
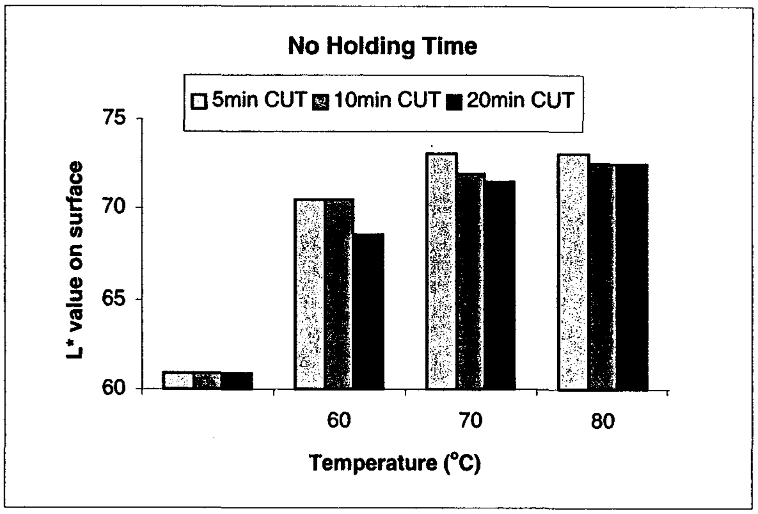
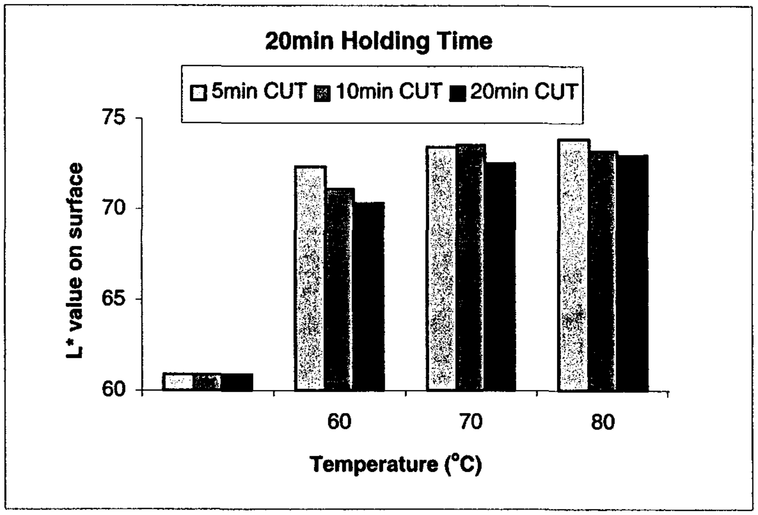


Figure 5.2 L* value at the center (Internal) of ham emulsions subjected to ohmic heating under different conditions





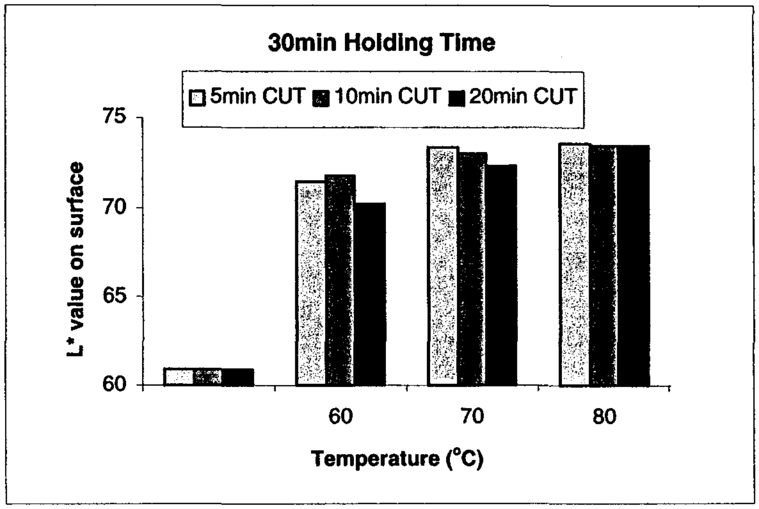


Figure 5.3 L* value on the surface (External) of ham emulsions subjected to ohmic heating under different conditions

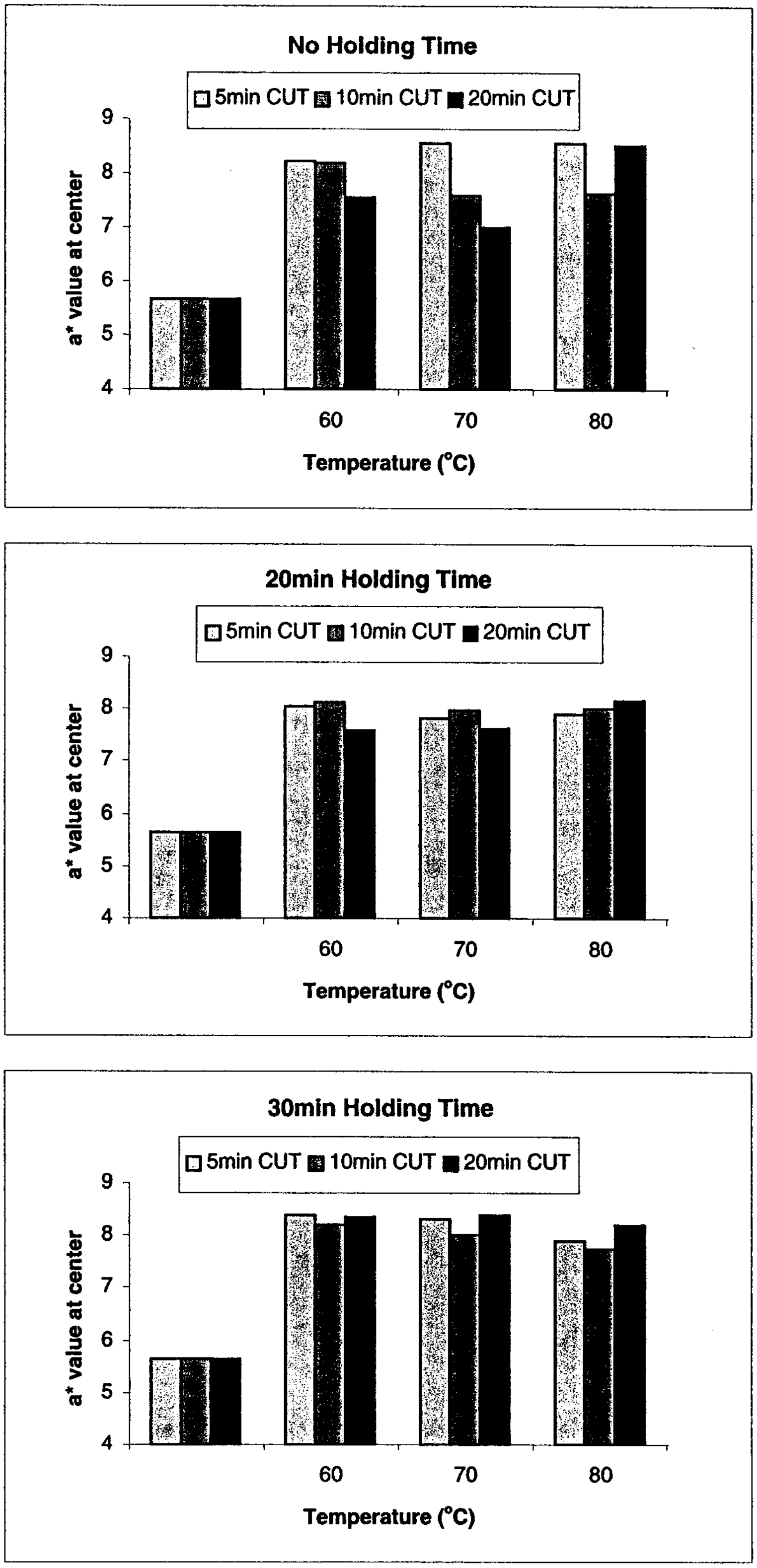


Figure 5.4 a* value at the center (Internal) of ham emulsions subjected to ohmic heating under different conditions

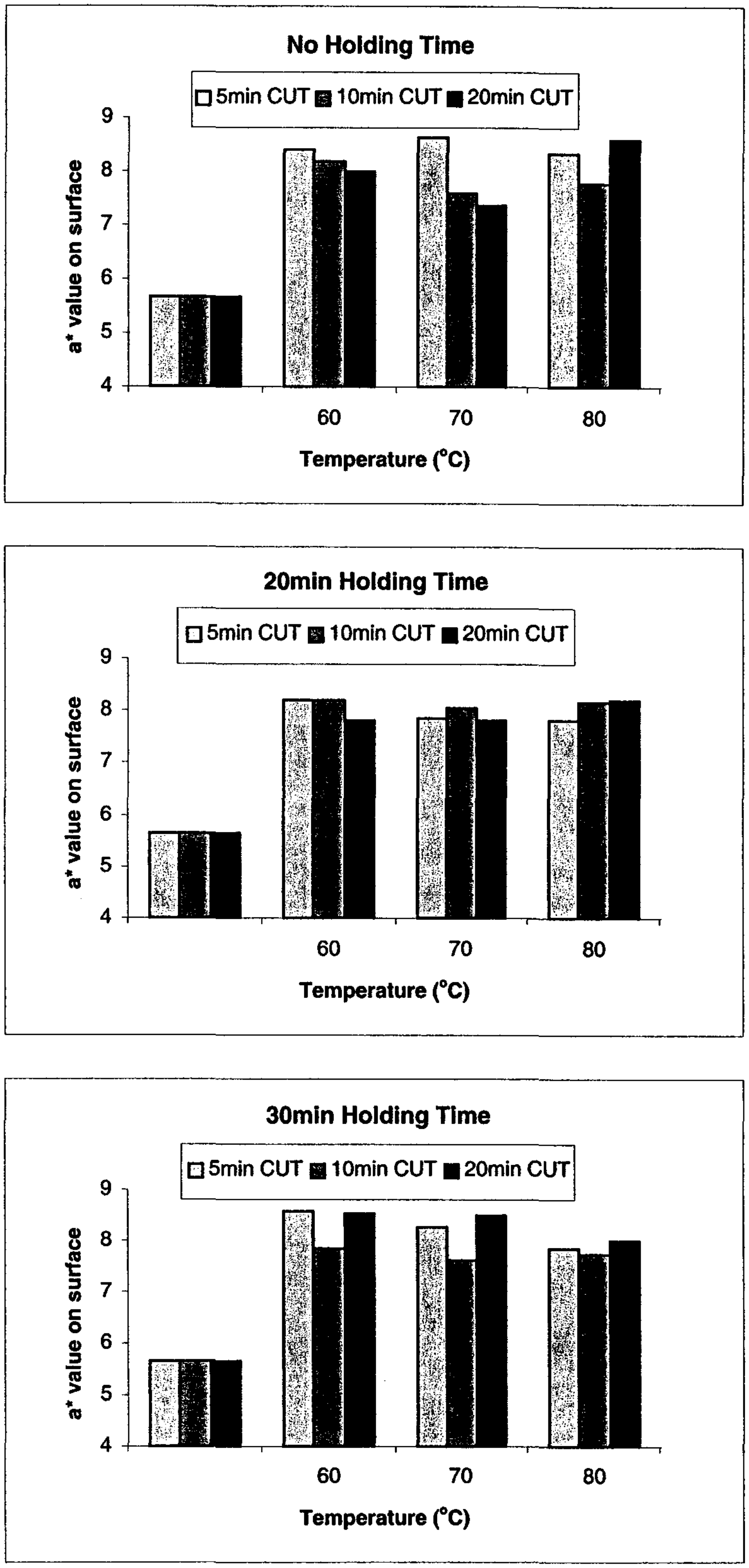


Figure 5.5 a* value on the surface (External) of ham emulsions subjected to ohmic heating under different conditions

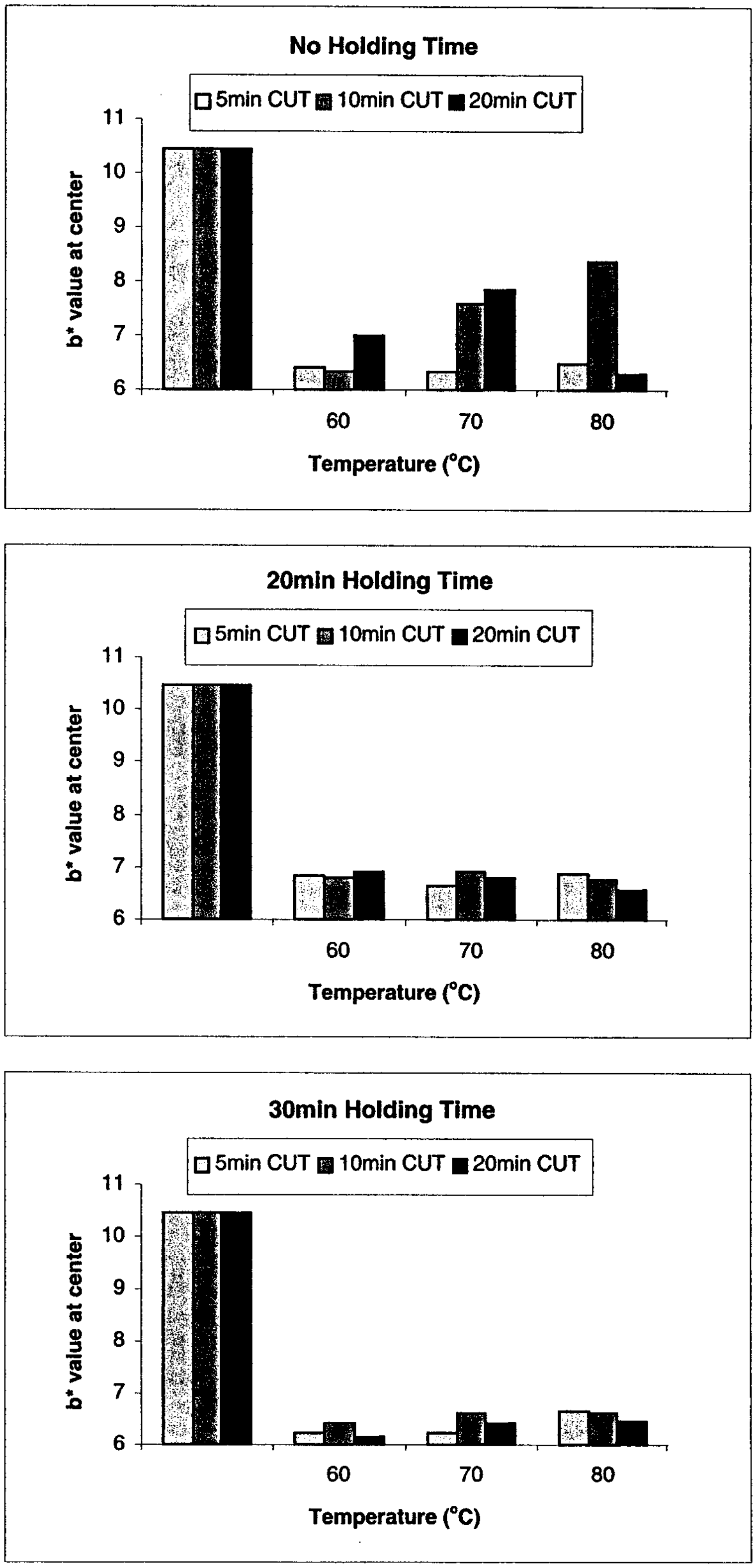


Figure 5.6 b* value at the center (Internal) of ham emulsions subjected to ohmic heating under different conditions

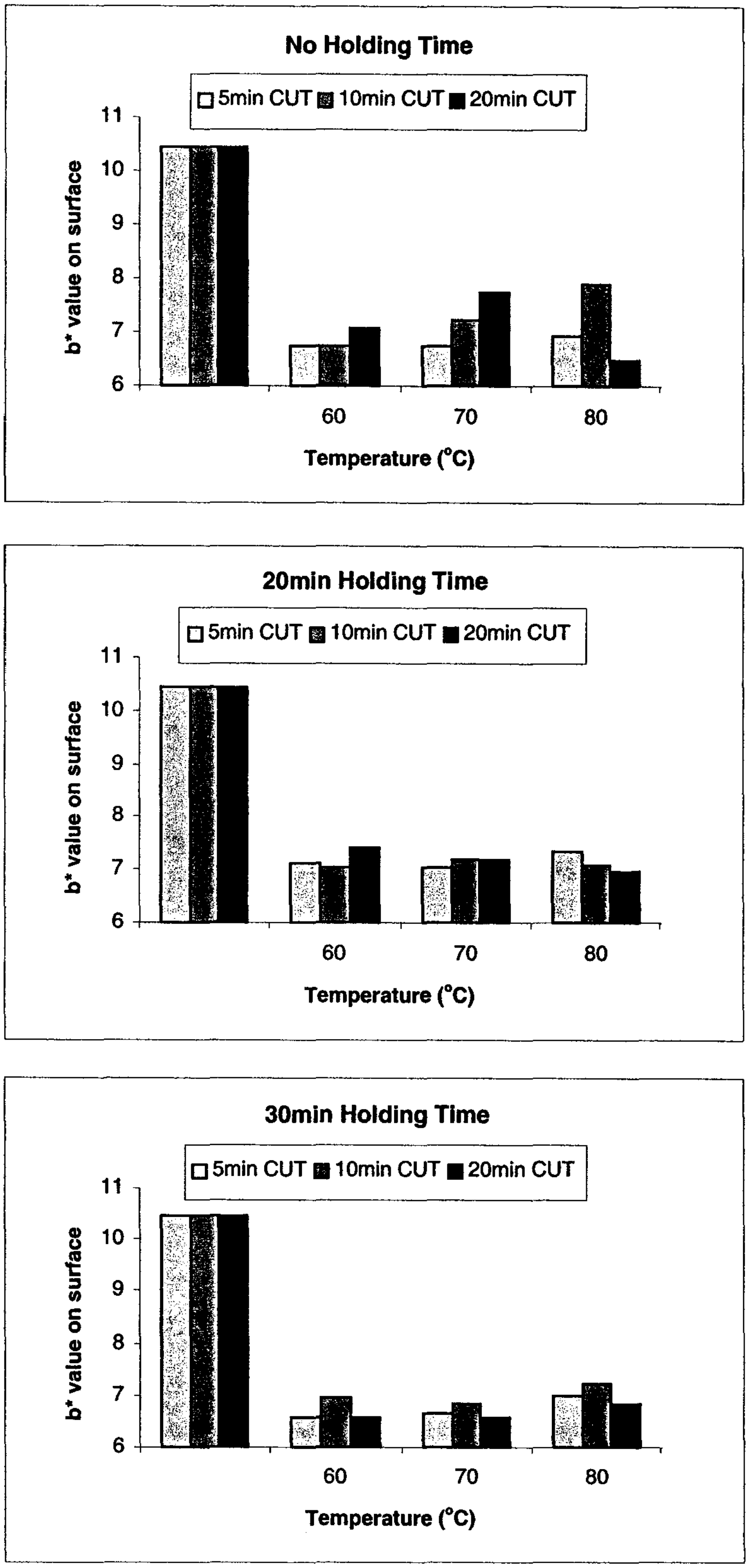


Figure 5.7 b* value on the surface (External) of ham emulsions subjected to ohmic heating under different conditions

Table 5.1 Mean effects table for color parameters (n=216)

		L* value		**a* value**		**b* value**	
		Internal	**Surface**	**Internal**	**Surface**	**Internal**	**Surface**
Temperature (°C)	60	69.26a	70.72a	8.08a	8.28a	6.56a	6.90a
	70	70.84b	72.42b	7.92b	7.96a	6.83a	7.02b
	80	71.26c	73.18c	8.06a	8.05a	6.79b	7.05b
Come Up Time (min)	5	70.86a	72.74a	8.19a	8.21a	6.52a	6.89a
	10	70.63b	71.99b	7.94b	7.99a	6.94b	7.12b
	20	69.88b	71.59c	7.93b	8.09a	6.72c	6.98c
Holding Time (min)	0	69.69a	71.58a	7.97a	8.10a	6.97a	7.03a
	20	70.88b	72.60b	7.92a	8.01a	6.79b	7.16b
	30	70.79c	72.14b	8.17b	8.18a	6.42c	6.80c

Means for the different levels of a given variable not sharing the same letter within a column are significantly different by Duncan's multiple range at the 5% level.

Table 5.2 Analysis of variance of the factors influencing the color values at the center and on the surface of ohmic processed fine ham emulsions

Factors	L* value		a* value		b* value	
	Internal	Surface	Internal	Surface	Internal	Surface
Main Effects						
T	*	*	*	ns	*	*
CUT	ns	*	*	ns	*	*
Ho	*	*	*	ns	*	*
Interactions						
T x CUT	ns	*	*	ns	*	*
T x Ho	*	*	*	ns	*	*
CUT x Ho	*	ns	*	ns	*	*
T x CUT x Ho	ns	*	*	ns	*	*

T: Temperature, CUT: Come-up time, Ho: Holding time

* significant at the 0.05 level

ns not significant at the 0.05 level

the average a* value of the raw product. The influence of parameters was somewhat mixed up. Shorter come-up time with longer holding times resulted in slightly higher a*-value on both internal and external surface of the samples similar to those observed in other studies (Koutchma *et al.*, 2000; Piette *et al.*, 1997c).

With b*-values of both internal and surface color reading, the associated changes were small. Higher temperature and shorter holding time gave a slightly higher b* values. Intermediate come-up time also had a slightly larger b*. The b* values of all the ohmically processed samples were lower than the average b* value of the raw product.

5.4.1.3. Texture

Figure 5.8 to 5.12 show changes in several texture parameters (hardness, cohesiveness, springiness, gumminess and chewiness) of cooked fine ham emulsion as affected by cooking temperature (60-80°C), come up time (5-20 min) and holding period (0-20 min) under ohmic heating conditions. The mean effect values and their statistical significance are summarized in Tables 5.3 and 5.4. The various textural attributes showed somewhat similar results, somewhat more clear-cut than the color changes. The hardness of cooked samples showed a very clear and consistent trend (Figure 5.8) demonstrating an increase in value with temperature and come-up time, and holding period (Table 5.3). This showed the hardness formation to follow the traditional trend which depended on the cooking severity which should increase with temperature and holding time. The results

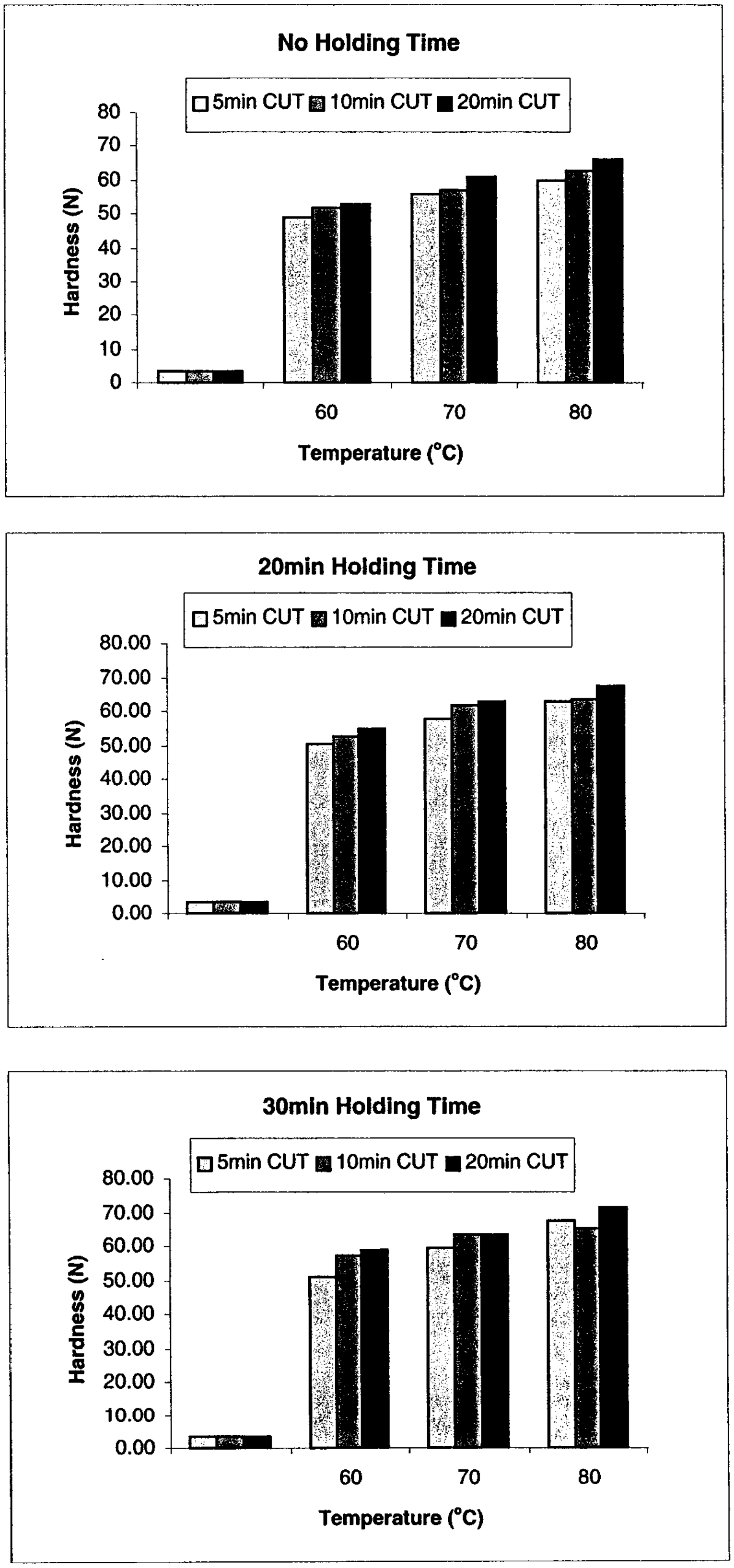


Figure 5.8 Hardness of ham emulsions subjected to ohmic heating under different conditions

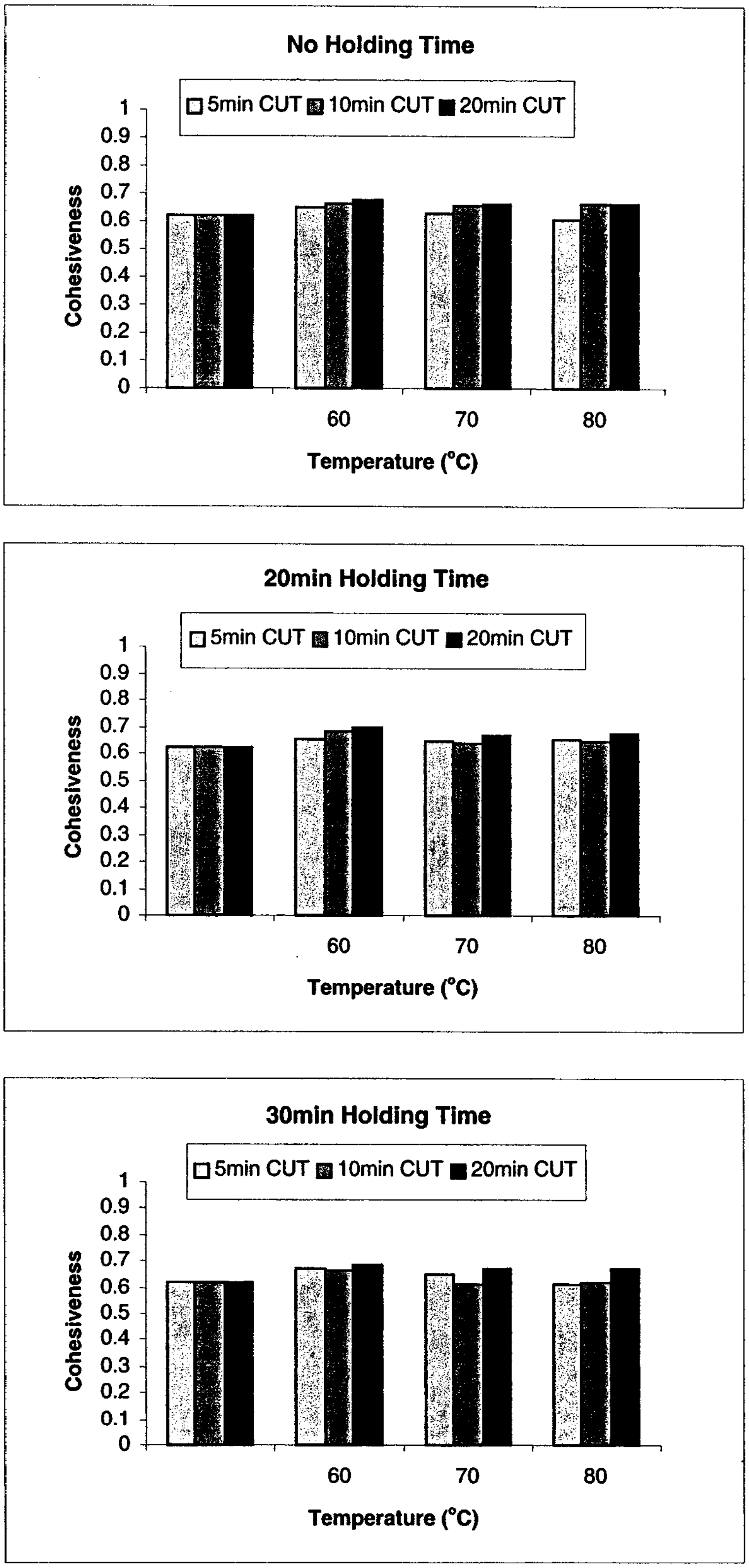


Figure 5.9 Cohesiveness of ham emulsions subjected to ohmic heating under different conditions

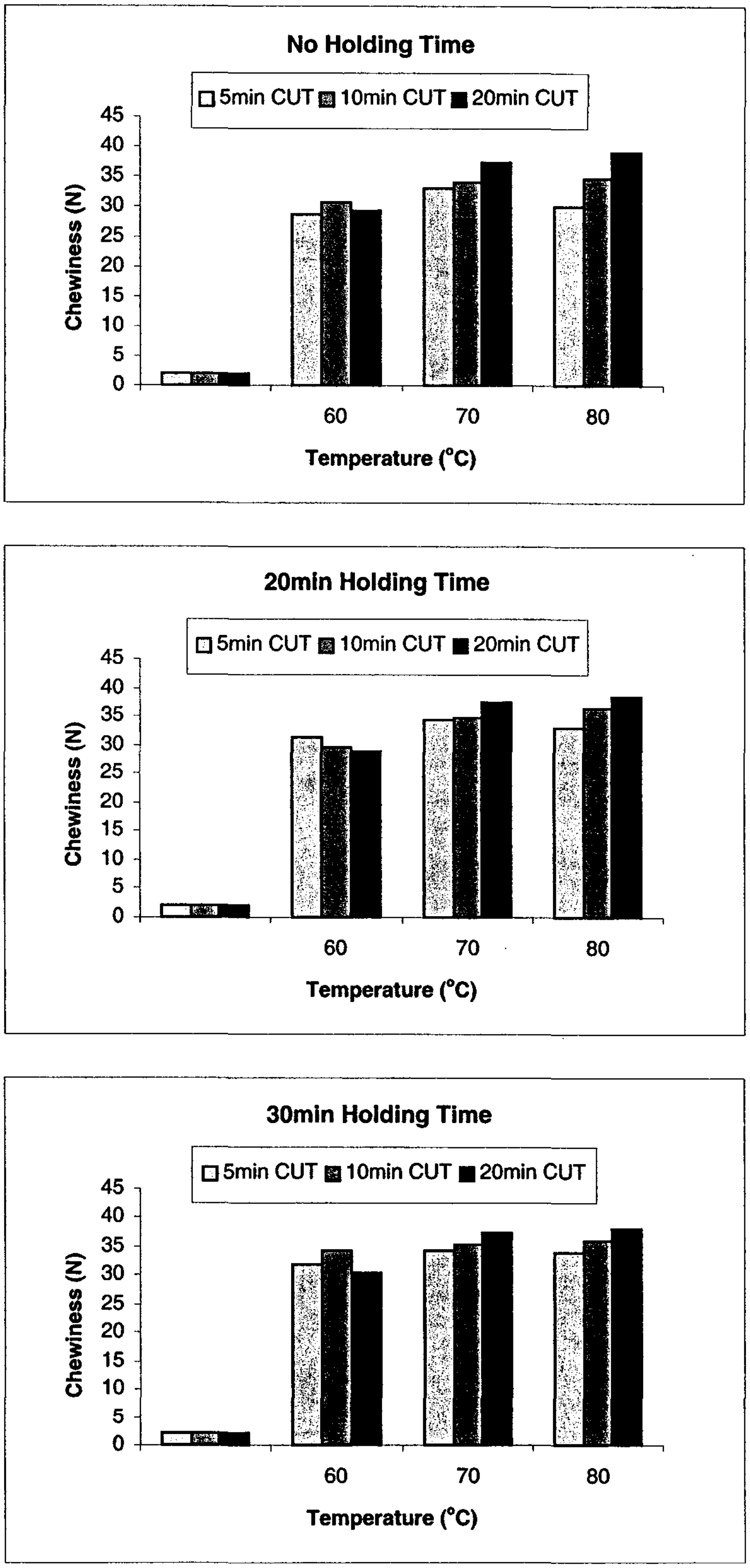


Figure 5.10 Chewiness of ham emulsions subjected to ohmic heating under different conditions

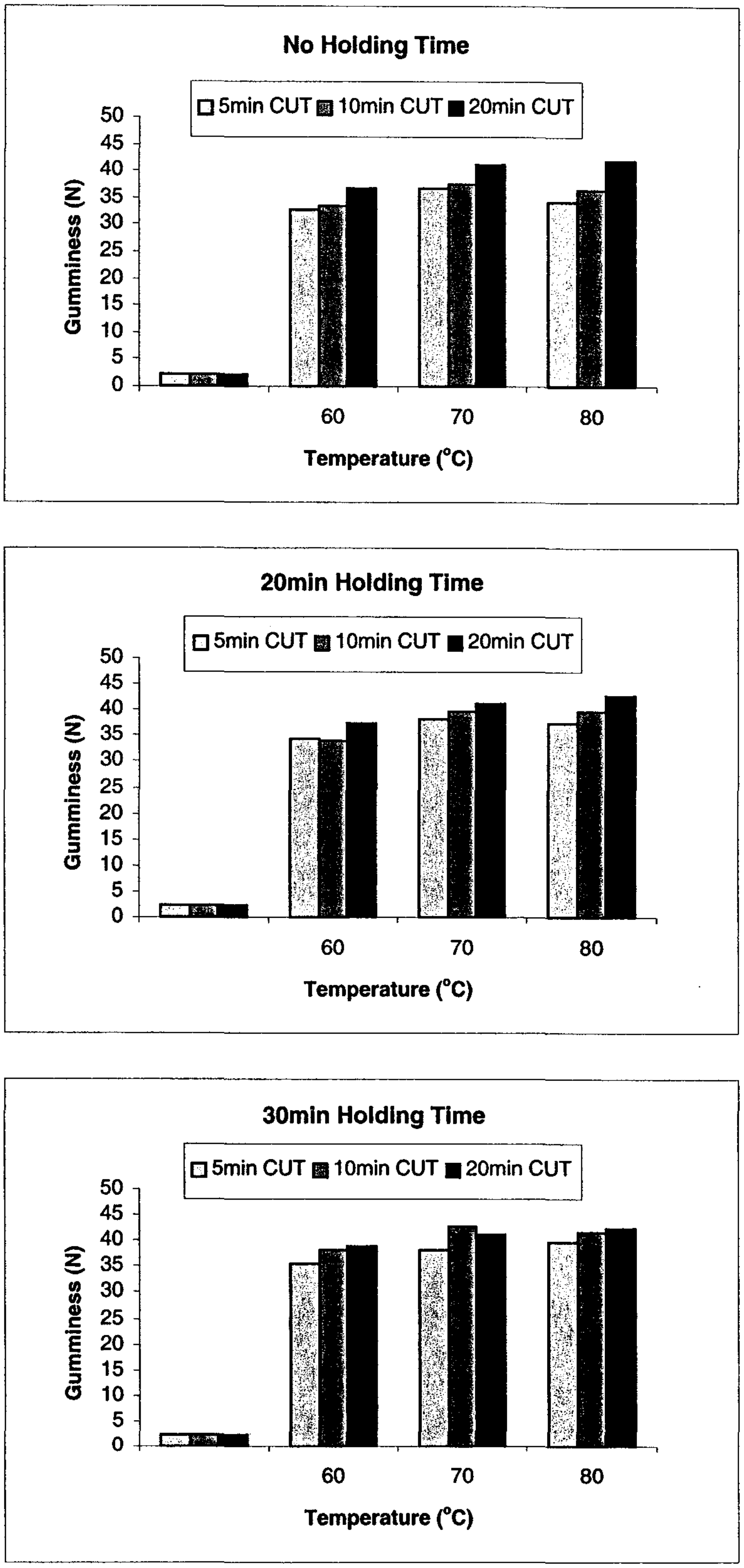


Figure 5.11 Gumminess of ham emulsions subjected to ohmic heating under different conditions

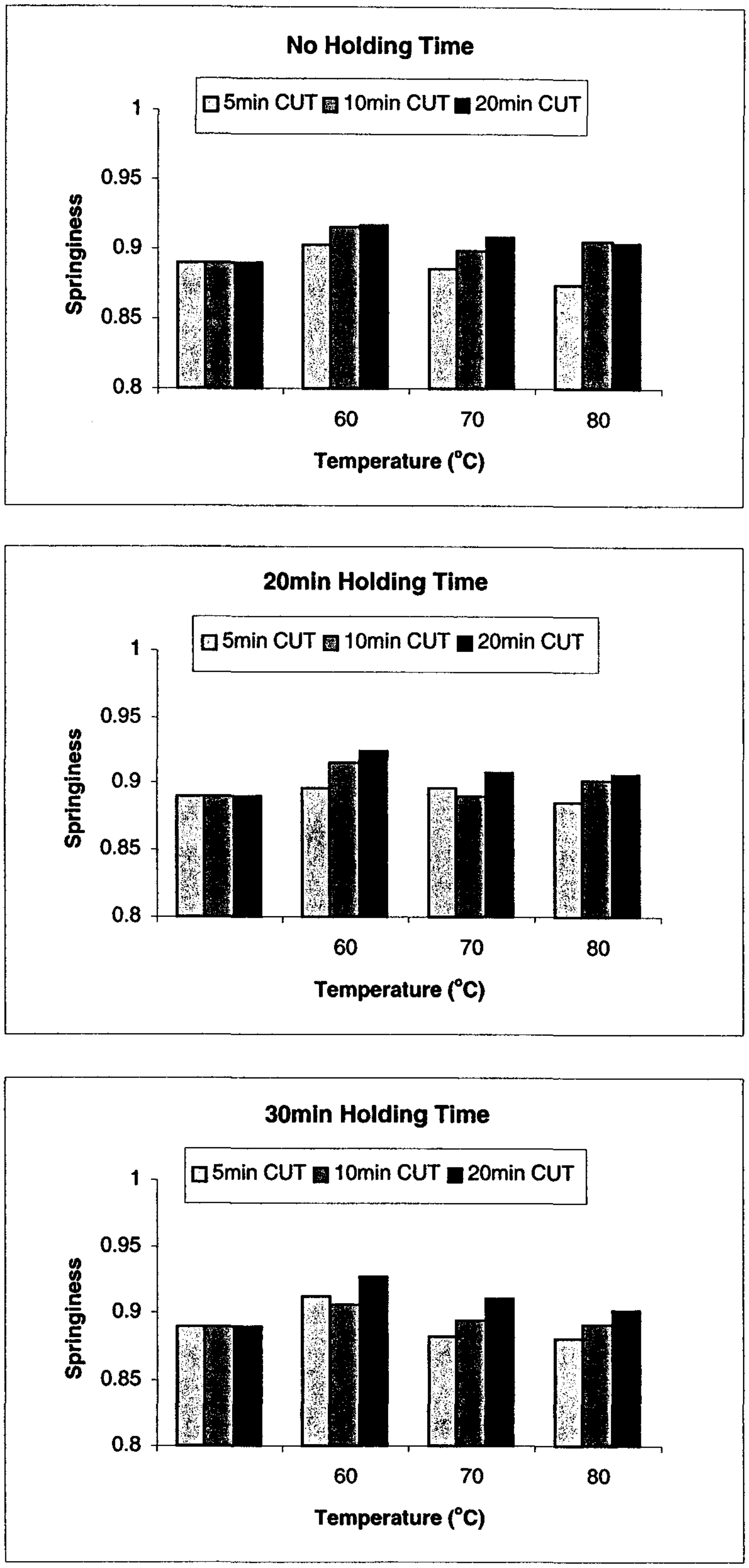


Figure 5.12 Springiness of ham emulsions subjected to ohmic heating under different conditions

Table 5.3 Mean effect table for texture parameters (n=103)

		Hardness (N)	**Cohesiveness**	**Chewiness (N)**	**Gumminess (N)**	**Springiness**
Temperature (°C)	60	53.27a	0.6735a	30.51a	33.86a	0.9132a
	70	60.23b	0.6554b	33.95b	37.96b	0.8984b
	80	65.21c	0.6457b	34.17b	38.33b	0.8949b
Come Up Time (min)	5	57.15a	0.6447a	30.50a	34.82a	0.8922a
	10	59.42a	0.6556b	32.77b	36.46b	0.9023b
	20	62.14b	0.6743c	35.36c	38.86c	0.9121c
Holding Time (min)	0	57.35a	0.6562a	32.89a	36.57a	0.9014a
	20	59.28a	0.6628b	33.45a,b	37.27b	0.9028a
	30	62.08b	0.6556a	32.29b	36.31c	0.9024a

Means for the different levels of a given variable not sharing the same letter within a column are significantly different by Duncan's multiple range at the 5% level.

Table 5.4 Analysis of variance of the factors influencing the texture values of ohmic processed fine ham emulsion

Factors	Hardness	Cohesiveness	Chewiness	Gumminess	Springiness
Main Effects					
T	*	*	*	*	*
CUT	*	*	*	*	*
Ho	*	*	ns	*	ns
Interactions					
T x CUT	ns	ns	*	ns	*
T x Ho	ns	*	ns	ns	ns
CUT x Ho	ns	*	ns	ns	*
T x CUT x Ho	ns	ns	ns	ns	ns

T: Temperature, CUT: Come-up time, Ho: Holding time

* significant at the 0.05 level

ns not significant at the 0.05 level

also indicated that the possible texture at any given temperature was largely developed at the end of come-up period. The actual value was nevertheless lower for that cooked at 60°C (49-59N) as compared to that at 80°C (60-72N). Other texture parameters showed somewhat similar results except that with respect to chewiness and springiness, hold time effect was not significant ($p>0.05$) (Table 5.4). The cohesiveness and springiness values were nearly the same as in the raw emulsion. Beside the temperature and come-up time, the hardness (Figure 5.8) was influenced ($p<0.05$) by the interactions of come-up time x holding time. The cohesiveness (Figure 5.9) was influenced ($p<0.05$) by the holding time, and interactions of temperature x holding time, come-up time x holding time, and temperature x come-up time x holding time; the chewiness (Figure 5.10) was influenced ($p<0.05$) by the interactions of temperature x come-up time, and temperature x come-up time x holding time. The gumminess (Figure 5.11) was influenced ($p<0.05$) by the interactions of temperature x come-up time; and the springiness (Figure 5.12) was influenced ($p<0.05$) the interactions of temperature x come-up time, and come-up time x holding time.

Overall, based on the texture profile analysis, it could be generalized that the processed products were more firm, more gummy and more chewy than the raw fine ham emulsion. Come-up time and temperature, and their interactions were more significant with respect to the different texture parameters. No published information is available for comparison. As was indicated earlier, some studies on fish proteins indicate the ohmic heating to offer an advantage over conventional heating (Yongsawatdigul *et al.,* 1995a,b; Park *et al.,* 1995,1998).

5.4.1.4. Cooking loss, water holding capacity and water activity

Figures 5.13 to 5.15 show the effects of different ohmic heating treatments on the associated cooking loss, water holding capacity and water activity. Table 5.5 shows the means and their significance and Table 5.6 summarized the analysis of variance results. Cooking loss ranged from 0.36 – 1.1 % depending on the temperature, come-up time and the length of the holding period. Water holding capacity slightly decreased with temperature, the range of values being narrow (64 – 70 %), and the water activity remained between 0.981 to 0.986.

In terms of statistical analysis of variance (Table 5.6), holding time effect was significant ($p<0.05$) for the cooking loss. Water holding capacity was significantly influenced ($p<0.05$) by temperature, come-up time, holding time and the interactions between temperature x come-up time, temperature x holding time, and come-up time x holding time. Temperature, interaction of come-up time x holding time and temperature x come-up time x holding time had an impact on water activity ($p<0.05$).

5.4.2. Ohmic vs. Conventional Heating:

5.4.2.1. Heating behavior

Typical time-temperature profile during the ohmic and conventional heating are compared in Figure 5.16. The ohmic heating time-temperature profile indicated an almost linear come-up time, while the conventional heating indicated a semi-logarithmic convex profile approaching the target temperature. In conventional heating methods, heat is transferred within the solid sample by

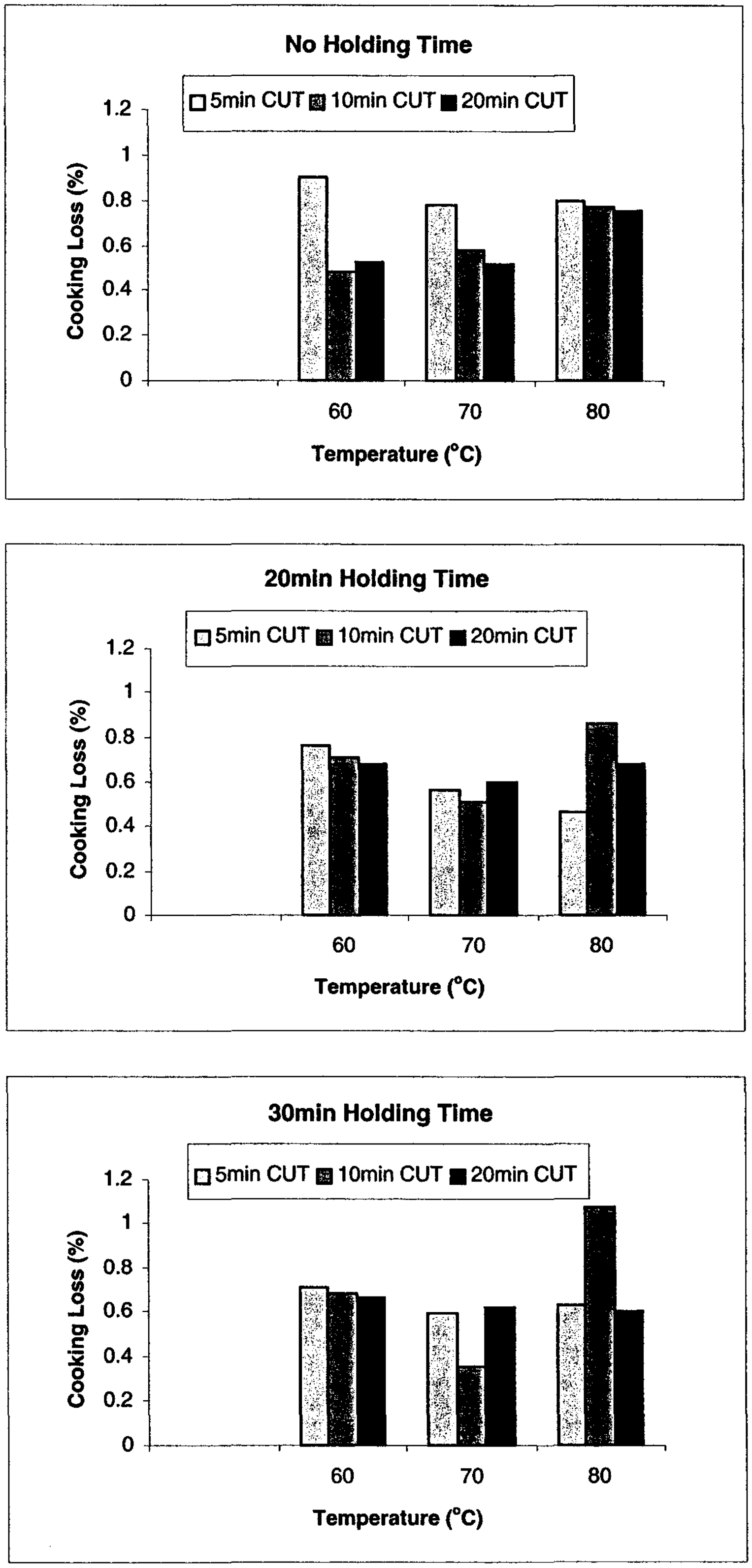


Figure 5.13 Cooking loss of ham emulsions subjected to ohmic heating under different conditions

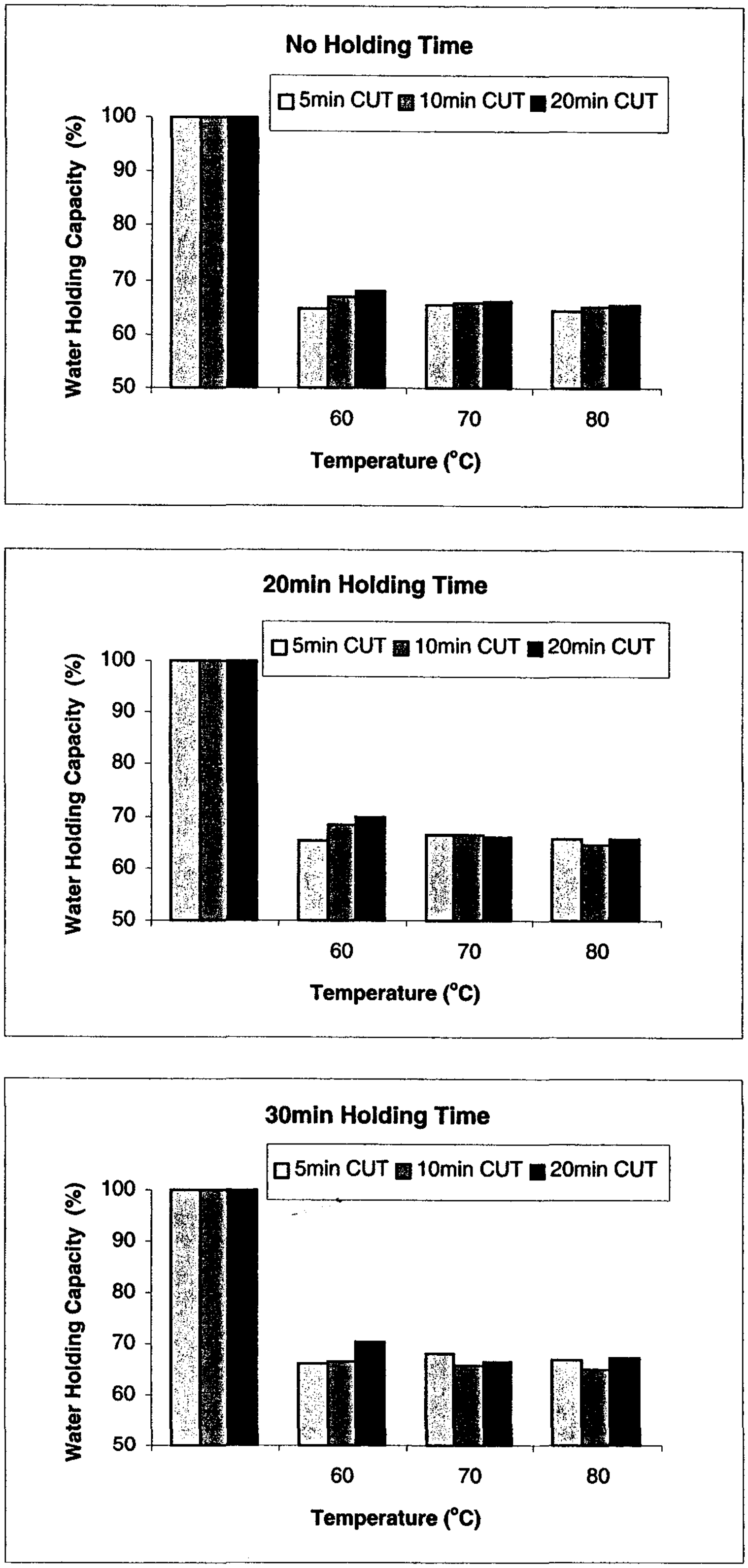


Figure 5.14 Water holding capacity of ham emulsions subjected to ohmic heating under different conditions

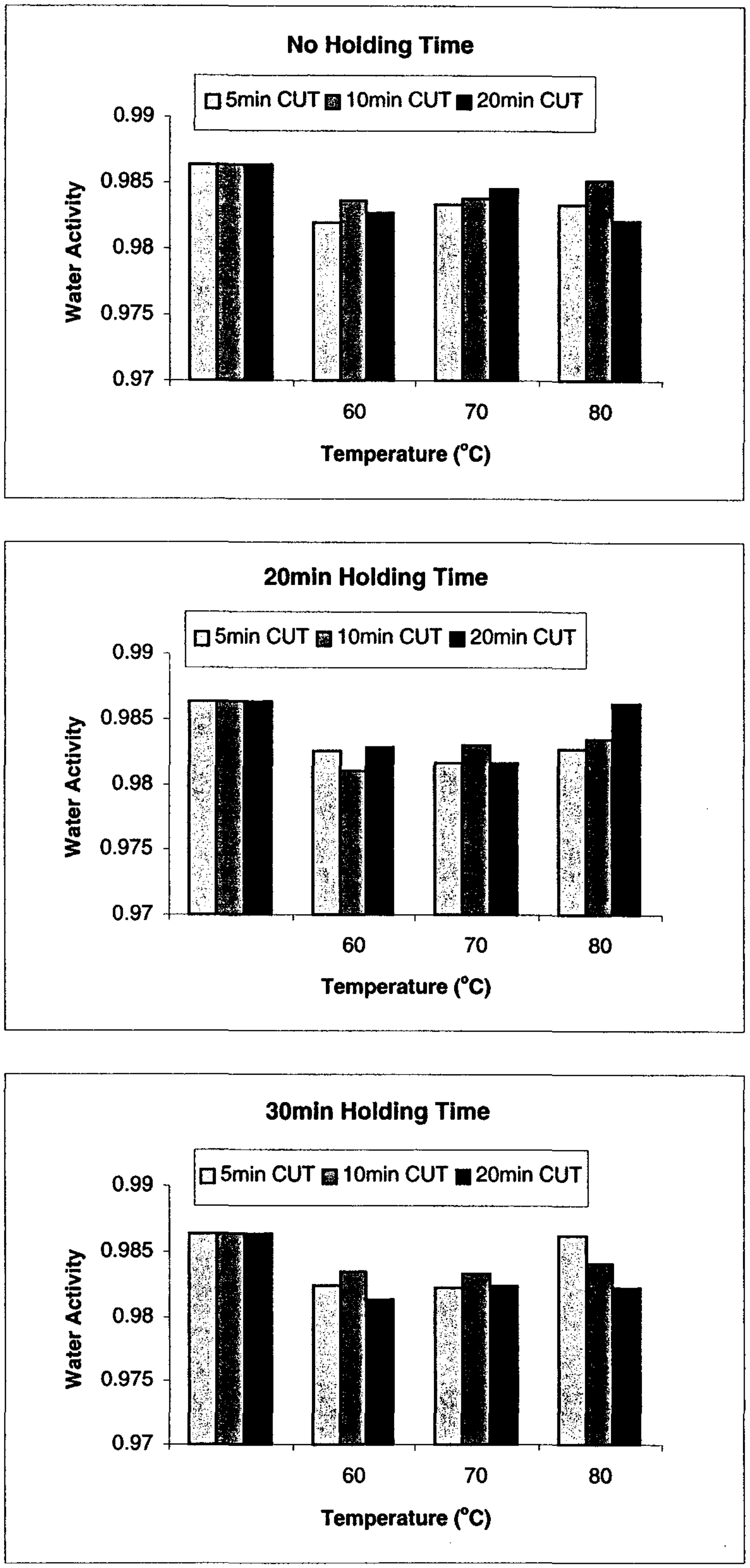


Figure 5.15 Water activity of ham emulsions subjected to ohmic Heating under different conditions

Table 5.5 Mean effects table for cooking loss, water holding capacity and water activity

		Cooking Loss (%) (N=17)	Water Holding Capacity (%) (N=36)	Water Activity (N=54)
Temperature (°C)	60	0.5844a	69.68a	0.9813a
	70	0.5211a	66.33b	0.9815a
	80	0.6278a	64.28b	0.9831b
Come Up Time (min)	5	0.6450a	65.68a,b	0.9817a
	10	0.6094a	66.72a	0.9826a
	20	0.4789a	67.89b	0.9817a
Holding Time (min)	0	0.7511a	66.67a	0.9820a
	20	0.4950a	67.39a,b	0.9822a
	30	0.4872a	66.23b	0.9817a

Means for the different levels of a given variable not sharing the same letter within a column are significantly different by Duncan's multiple range at the 5% level.

Table 5.6 Analysis of variance of the factors influencing the cooking loss, water holding capacity and water activity values of ohmic processed fine ham emulsion

Factors	Cooking Loss	WHC	A_w
Main Effects			
T	ns	*	*
CUT	ns	ns	ns
Ho	ns	ns	ns
Interactions			
T x CUT	ns	*	ns
T x Ho	ns	ns	ns
CUT x Ho	ns	ns	*
T x CUT x Ho	ns	ns	*

T: Temperature, CUT: Come-up time, Ho: Holding time

CL: cooking loss; WHC: water holding capacity; A_w: water activity

* significant at the 0.05 level

ns not significant at the 0.05 level

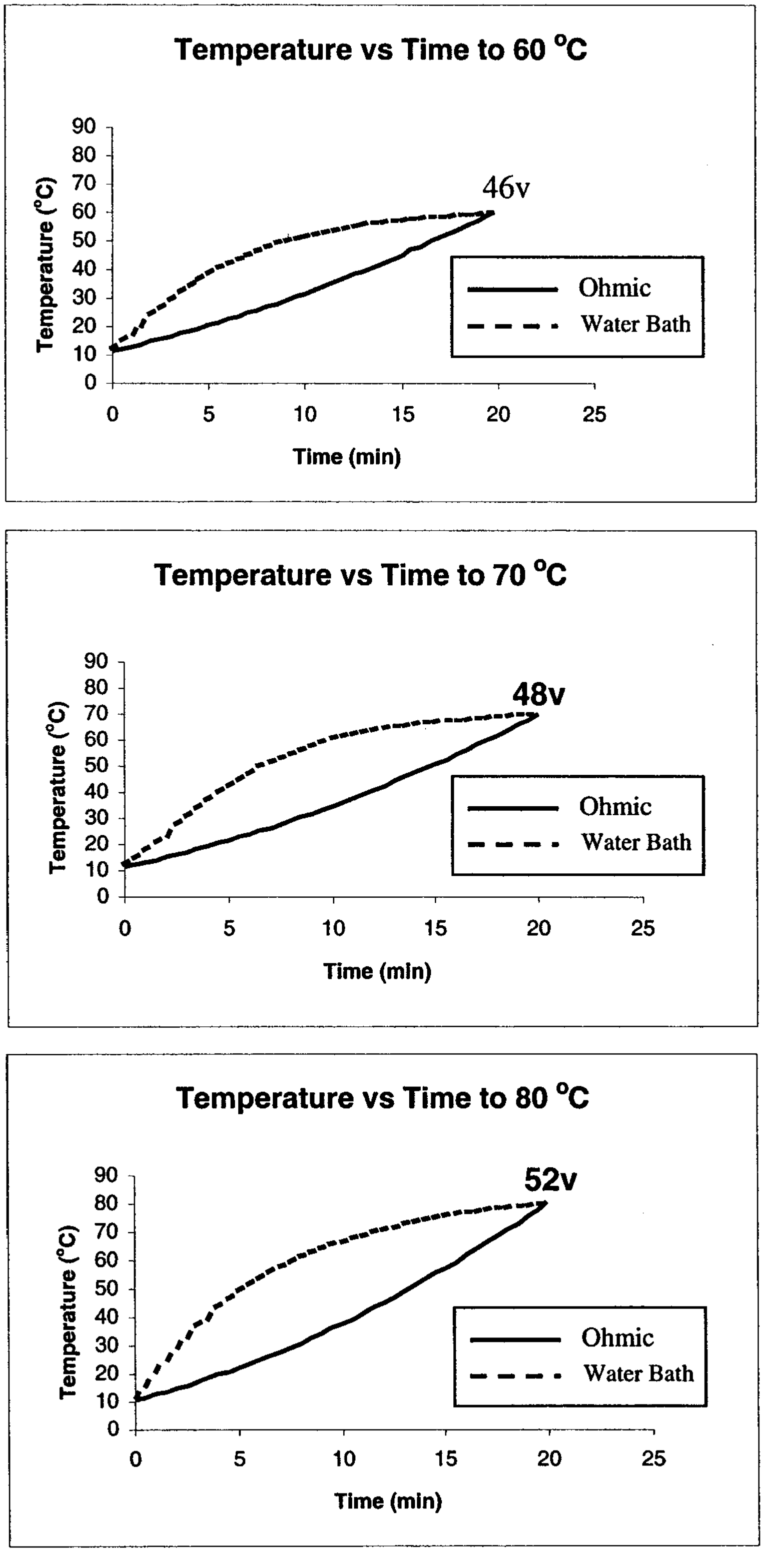


Figure 5.16 Temperature profile of ham emulsions subjected to ohmic and conventional heating conditions

means of conduction. Rate of conduction heat transfer is typically slow and depends on various factors such as temperature of heating medium, geometry, and thermal properties of the sample. In confirmation with Fourier's law, the time-temperature profile will fit a log-linear model when the logarithm of temperature difference between the medium and product is plotted against time. On a linear plot, this would simulate a convex curve with a more rapid rise in the beginning followed by a gradual approach to the target temperature. In agreement with Ohm's law, linear heating rates were achieved when using ohmic heating (Marcotte, 1999).

5.4.2.2. Color changes

Figures 5.17 to 5.22 and Table 5.7 show the tristimulus L*, a* and b* values both at the interior cut surface (Internal or Center) and on the outer surface (Surface) of fine ham emulsions subjects to ohmic and conventional heating. Compared to the conventional treatment, ohmic treated sample showed a significant difference in lightness factor – L* value. The results show that both conventional and ohmic heating resulted in a large increase in L* value as compared to that in the raw fine ham emulsion thereby by making the cooked product much "lighter". At each temperature and holding time (after a 20 min come-up time), the L* value of samples subjected to ohmic heating also had much larger L* than those heated by the conventional way (Figure 5.17). Similar results were observed with the surface color as demonstrated in Figure 5.18. As the process temperature increased, the margin of difference in L* value between

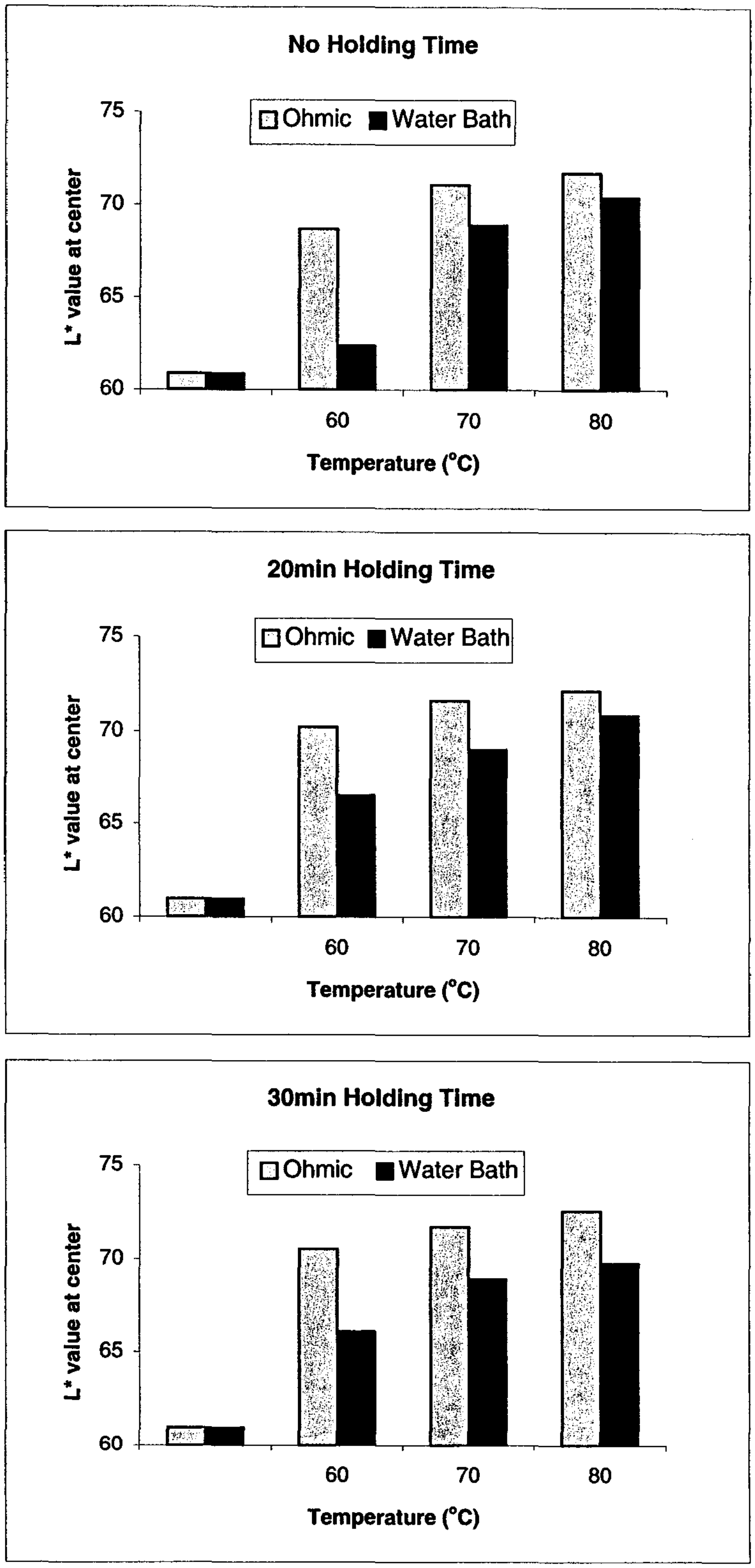


Figure 5.17 L* value at the center (Internal) of ham emulsions subjected to ohmic and conventional heating conditions

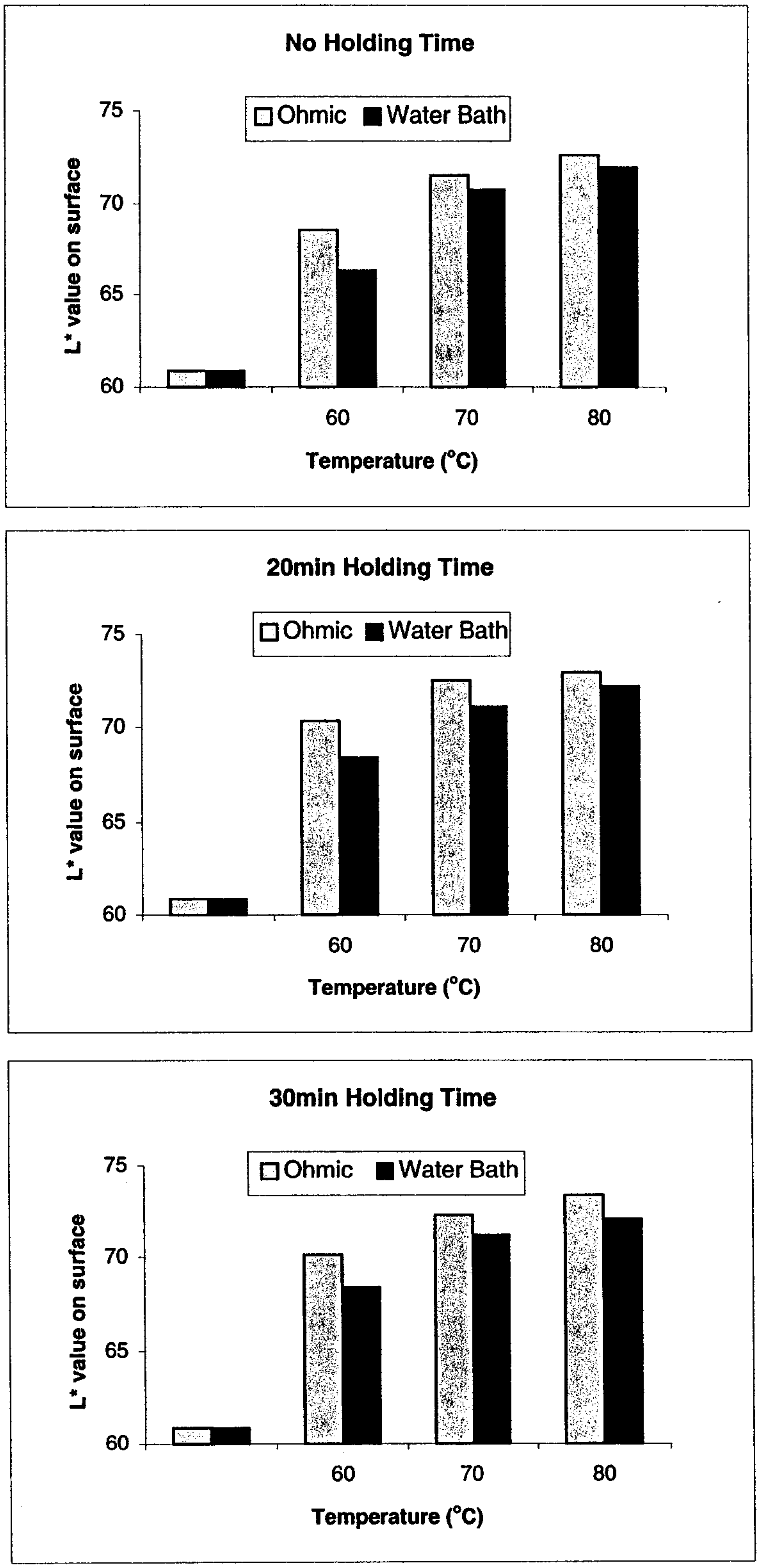


Figure 5.18 L* value on surface (External) of ham emulsions subjected to ohmic and conventional heating conditions

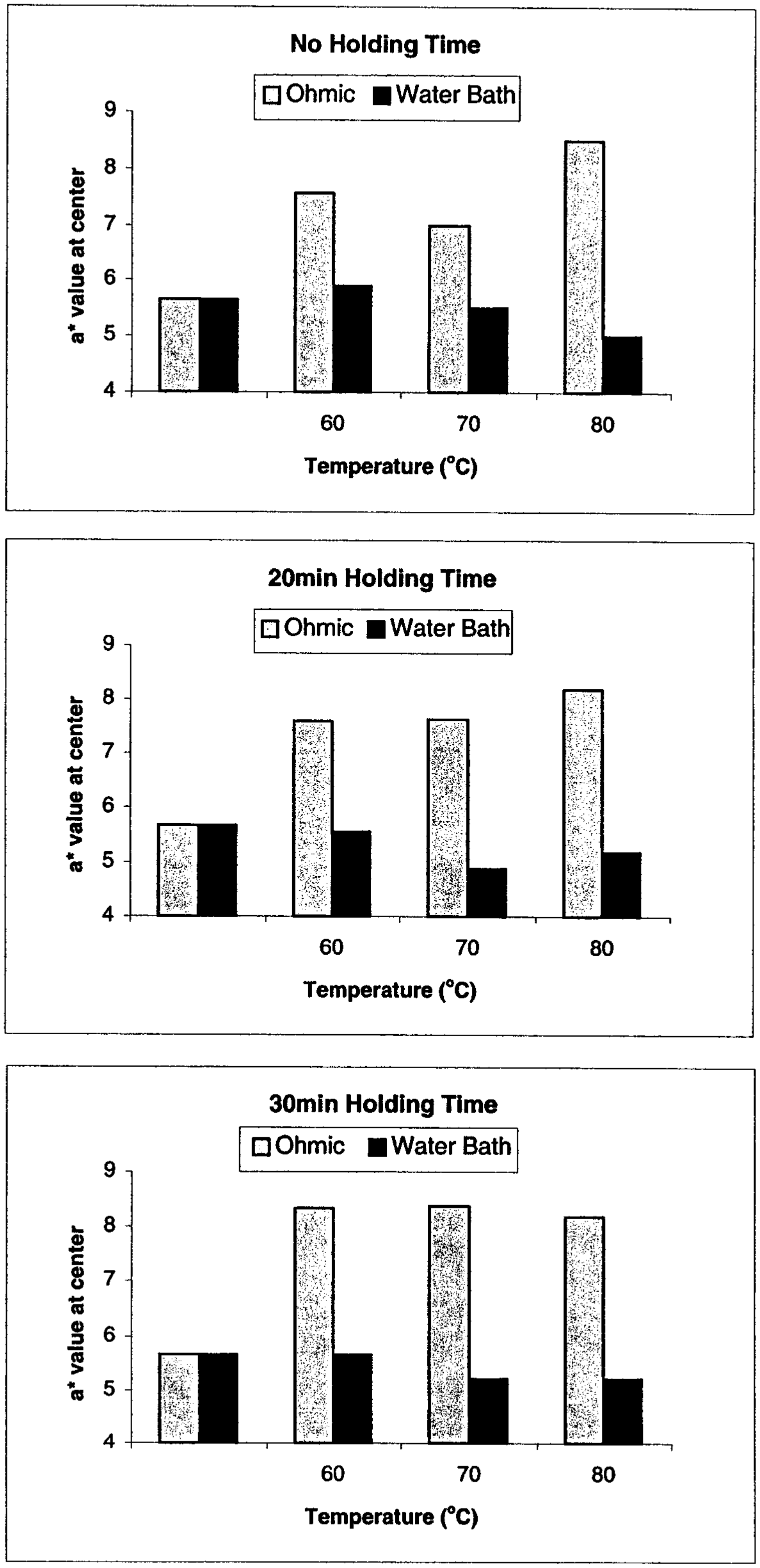


Figure 5.19 a* value at the center (Internal) of ham emulsions subjected to ohmic and conventional heating conditions

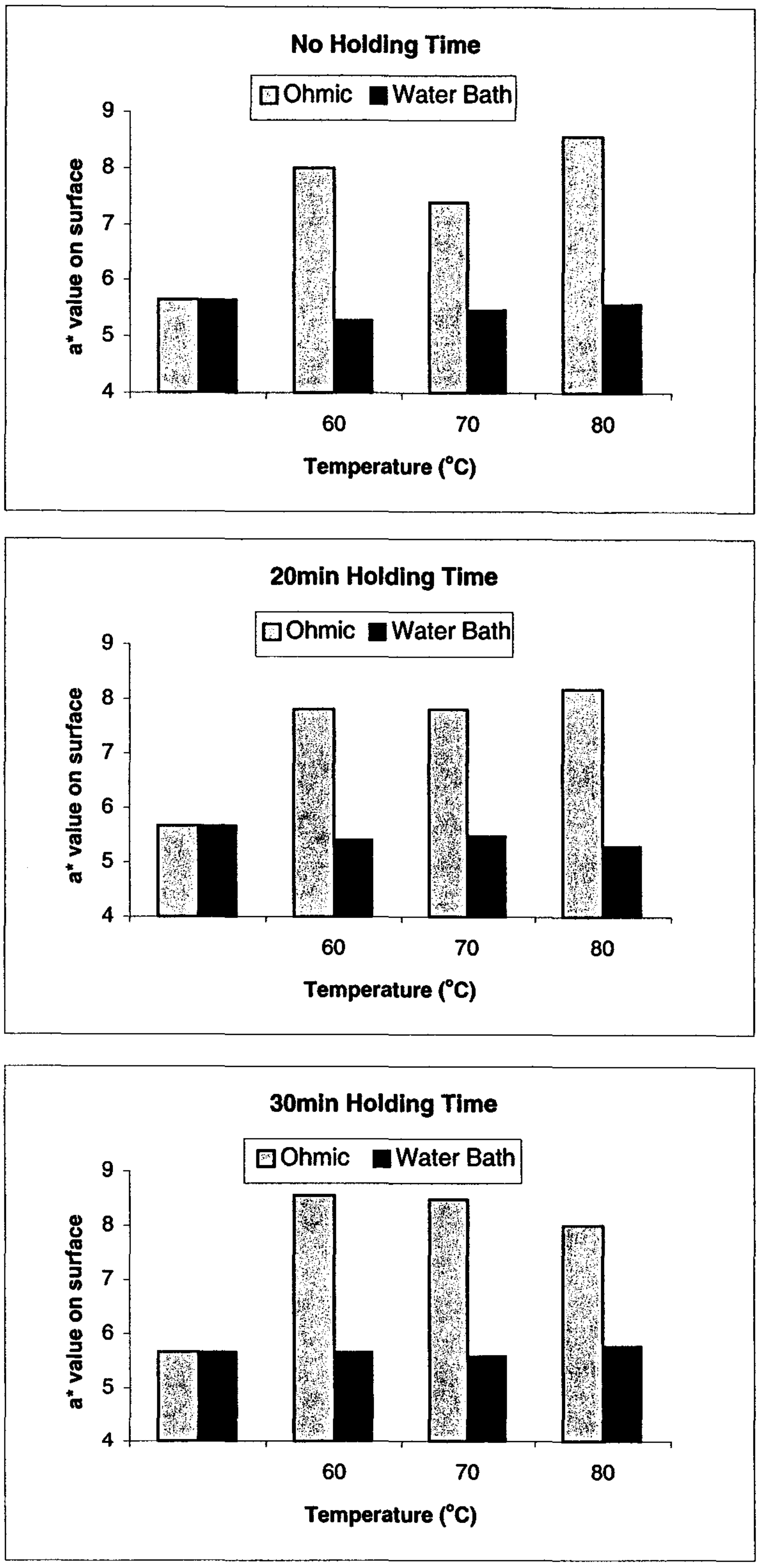


Figure 5.20 a* value on surface (External) of ham emulsions subjected to ohmic and conventional heating conditions

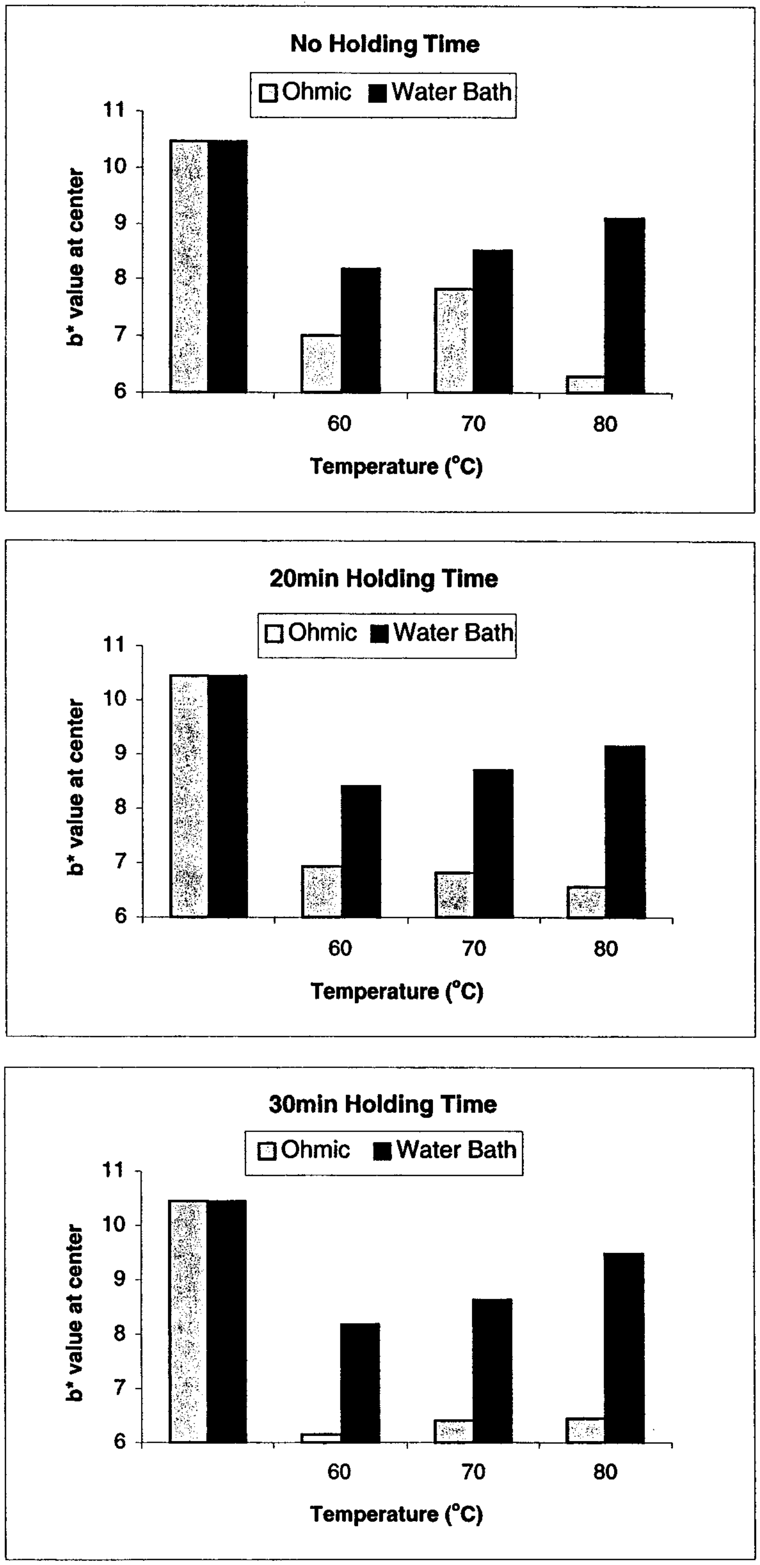


Figure 5.21 b* value at the center (Internal) of ham emulsions subjected to ohmic and conventional heating conditions

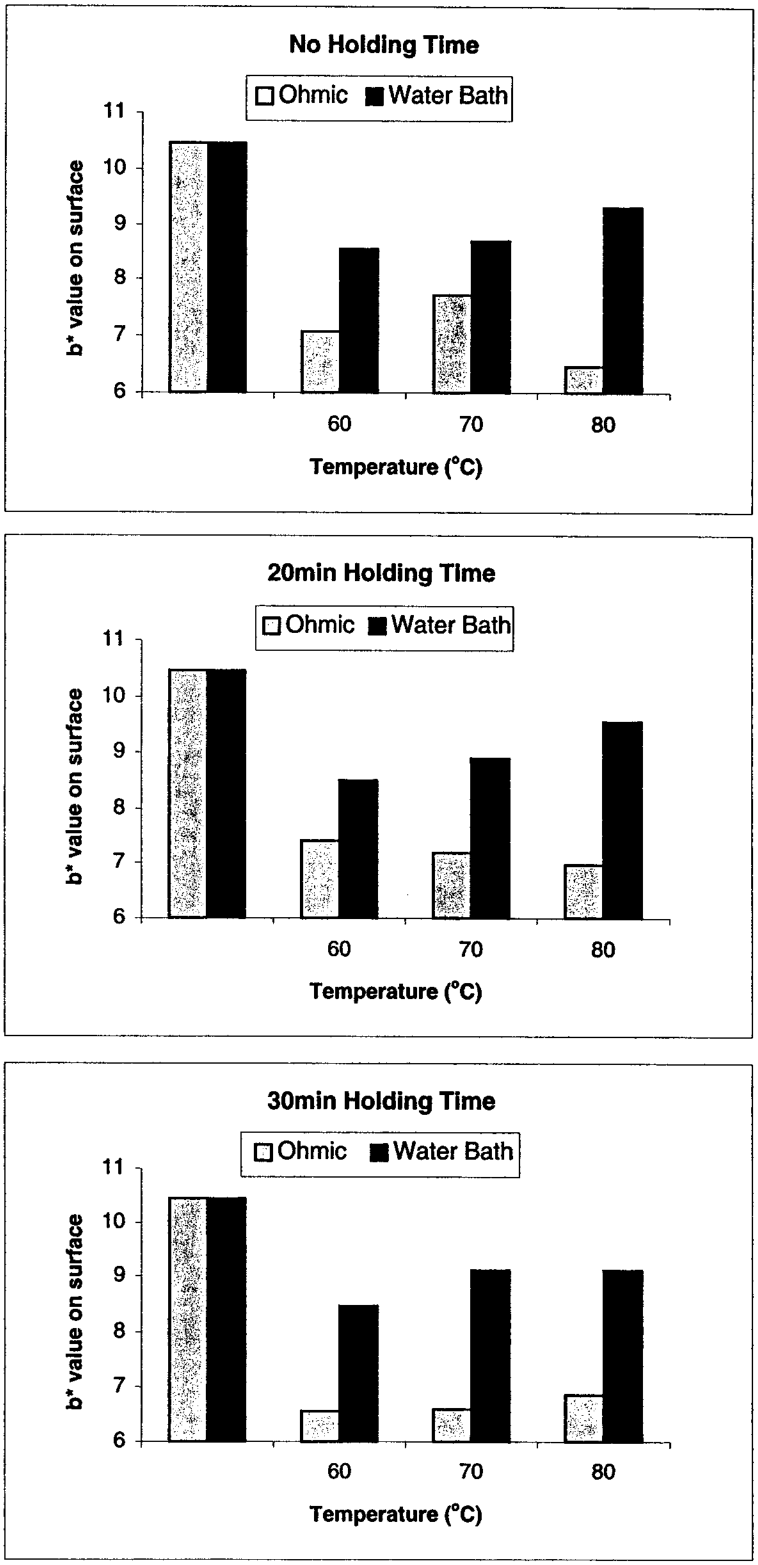


Figure 5.22 b* value on surface (External) of ham emulsions subjected to ohmic and conventional heating conditions

Table 5.7 Mean effects table for color parameters (N=46)

			L* value		**a* value**		**b* value**	
			Internal	**Surface**	**Internal**	**Surface**	**Internal**	**Surface**
Temperature (°C)	60	OHM	69.26a	70.72a	8.08a	8.28a	6.56a	6.90a
		CONV	65.12b	67.63b	5.64b	5.47b	7.73b	8.52b
	70	OHM	70.84a	72.42a	7.92a	7.96a	6.83a	7.02a
		CONV	69.03b	71.00b	4.63b	7.44b	8.91b	6.71b
	80	OHM	71.26a	73.18a	8.06a	8.05a	6.79a	7.05a
		CONV	69.85b	72.02b	4.95b	7.02b	9.24b	7.73b
Holding Time (min)	0	OHM	69.69a	71.58a	7.97a	8.10a	6.97a	7.03a
		CONV	67.46b	69.81b	4.96b	6.52b	8.61b	7.65b
	20	OHM	70.88a	72.60a	7.92a	8.01a	6.79a	7.16a
		CONV	68.48b	70.38b	5.12b	6.02b	8.53b	8.31b
	30	OHM	70.79a	72.14a	8.17a	8.18a	6.42a	6.80a
		CONV	68.05b	70.47b	5.13b	7.39b	8.75b	7.01b

OHM: Ohmic heating; CONV: Conventional heating. Means for the different levels of a given variable not sharing the same letter within a column are significantly different by Duncan's multiple range at the 5% level.

ohmic and conventionally heated samples gradually decreased.

The a* values (redness) of all the ohmic processed products (both on the surface and internal tissue – Figures 5.19 and 5.20) were again higher than the samples processed under conventional heating. Thus the ham emulsion may yield a "better redness" under the ohmic heating process. Compared to the raw ham emulsion, the surface a* values for the cooked samples were much higher. In the internal tissue, however, only samples the emulsions prepared under ohmic heating gave a* values higher than raw samples. Judge *et al.* (1989) also reported that the major change in color during cooking was an increase in redness "a* value" because of the transformation of myoglobin into the nitrosohaemochrome color. Compared to the control raw ham emulsion, a reduction was observed in b* values. Higher treatment temperatures gave a consistently higher b* values with conventional heating which was not observed with ohmically heated samples. The b* values of ohmic heated samples were lower than those of conventionally heat treated samples. Barbut and Mittal (1996) reported that the color changes in meat samples during heating is contributed by the presence of fat and proteins due to the formation of a coagulated protein enveloping the fat globules.

The analysis of variance results on all color parameters as affected by heat treatment under conventional and ohmic heating conditions are summarized in Table 5.8. In general, except for the L* value on the surface, all other parameters were influenced ($p<0.05$) by temperature, holding time and the method of heating (ohmic vs. conventional). The results also showed that the interaction between treatment x temperature, treatment x holding time, temperature x holding time,

Table 5.8 Analysis of variance of the factors influencing the color values at the center and on the surface of Ohmic and conventional processed fine ham emulsions

Factors	L* value		a* value		b* value	
	Internal	Surface	Internal	Surface	Internal	Surface
Main Effects						
Tr	*	*	*	*	*	*
T	*	*	*	*	*	*
Ho	*	*	*	*	*	*
Interactions						
Tr x T	*	*	*	ns	*	*
Tr x Ho	ns	ns	*	ns	*	*
T x Ho	*	*	*	*	*	*
Tr x T x Ho	*	ns	*	*	*	*

Tr: treatment; T: temperature; Ho: holding time

* significant at the 0.05 level

ns not significant at the 0.05 level

and, treatment x temperature x holding time of both processed significantly influenced ($p < 0.05$) the a* and b* values of the products. However, some factors and interactions did not show significant differences with respect to L* value.

5.4.2.3. Texture

Figures 5.23 to 5.27 show the changes in texture parameters of fine ham emulsion subjected to ohmic and conventional heating at different temperatures and holding times. Table 5.9 summarizes treatment means at different levels and their significance. Finally, the analysis of variance results are presented in Table 5.10.

The hardness of all cooked samples were higher than the raw emulsions. Hardness values increased with treatment temperatures and the samples subjected to ohmic heating were had slightly higher immediately after come-up but were nearly same as that of conventionally heated samples after the holding period. Cohesiveness was only marginally higher for the ohmically heated samples as compared to conventionally heated samples, with no major influence of temperature or holding time. The cohesiveness and gumminess of test samples increased slightly with temperature. There was no difference between conventional and ohmic heating. Springiness showed some differences, slightly decreasing with temperature for all samples. Several studies have shown that rapid heating methods, such as microwave and ohmic heating, have been effective to minimize textural degradation of fish muscle caused by endogenous heat stable proteases (Greene and Babbitt, 1990; Yongsawatdigul *et al.*, 1995;

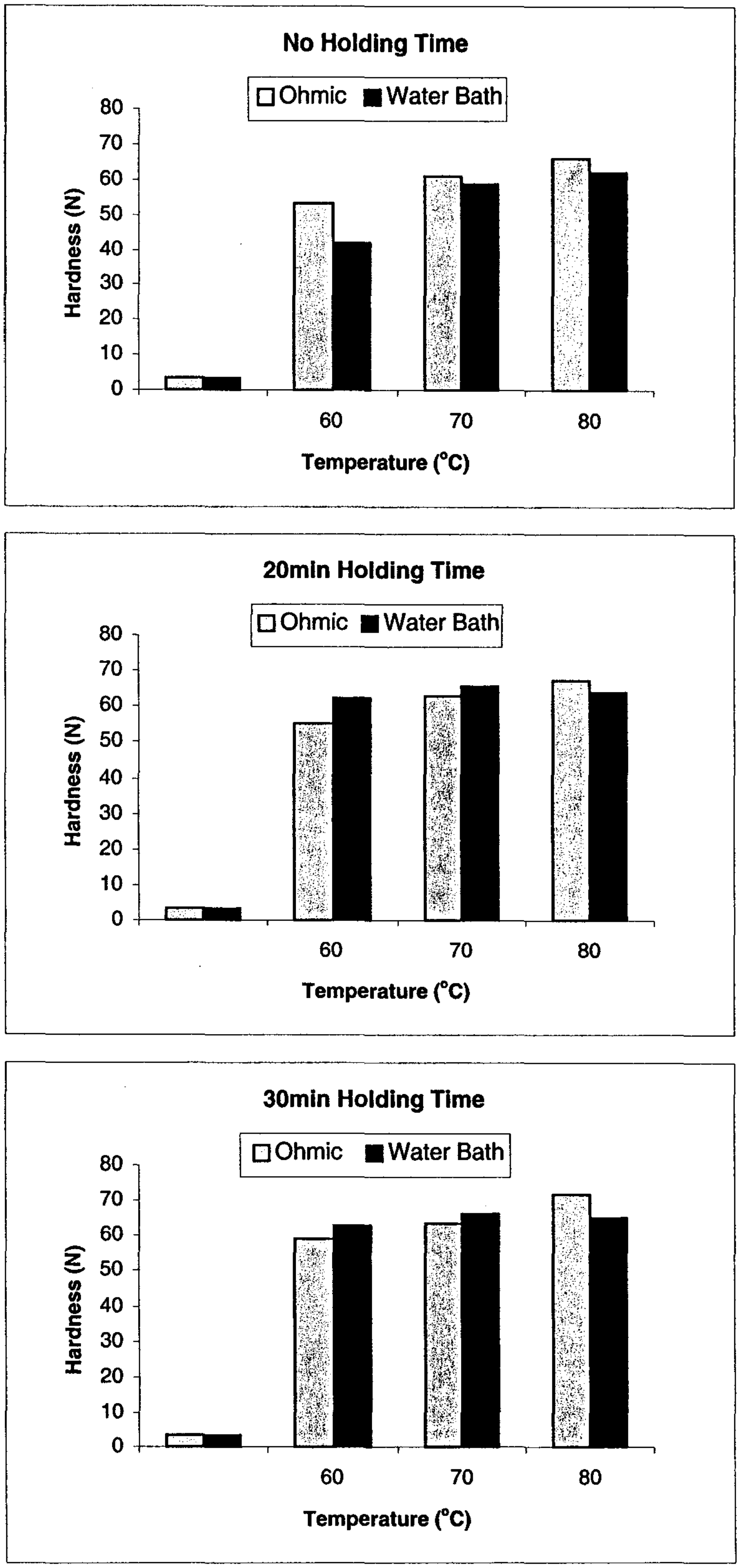


Figure 5.23 Hardness of ham emulsions subjected to ohmic and conventional heating conditions

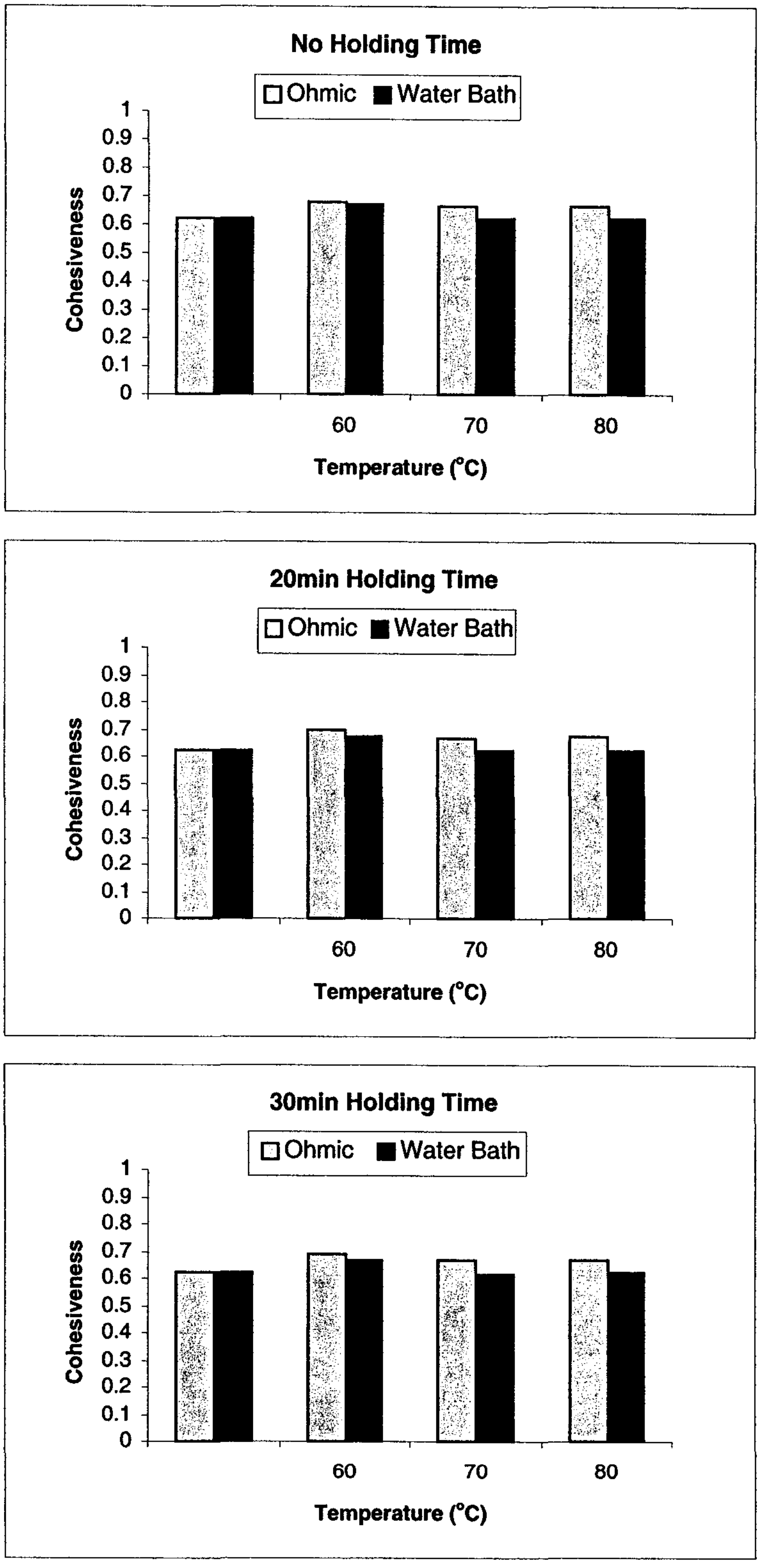


Figure 5.24 Cohesiveness of ham emulsions subjected to ohmic and conventional heating conditions

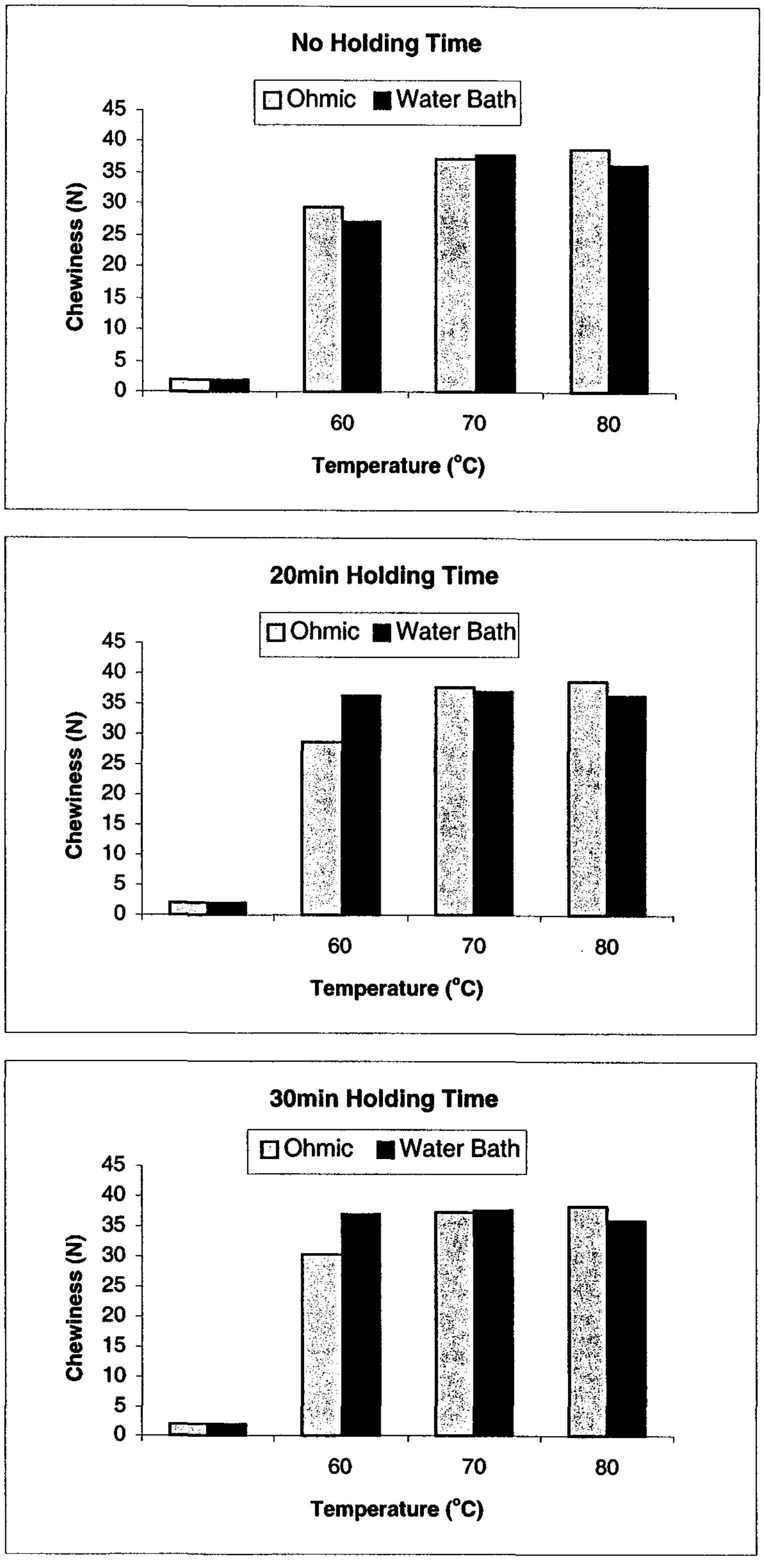


Figure 5.25 Chewiness of ham emulsions subjected to ohmic and conventional heating conditions

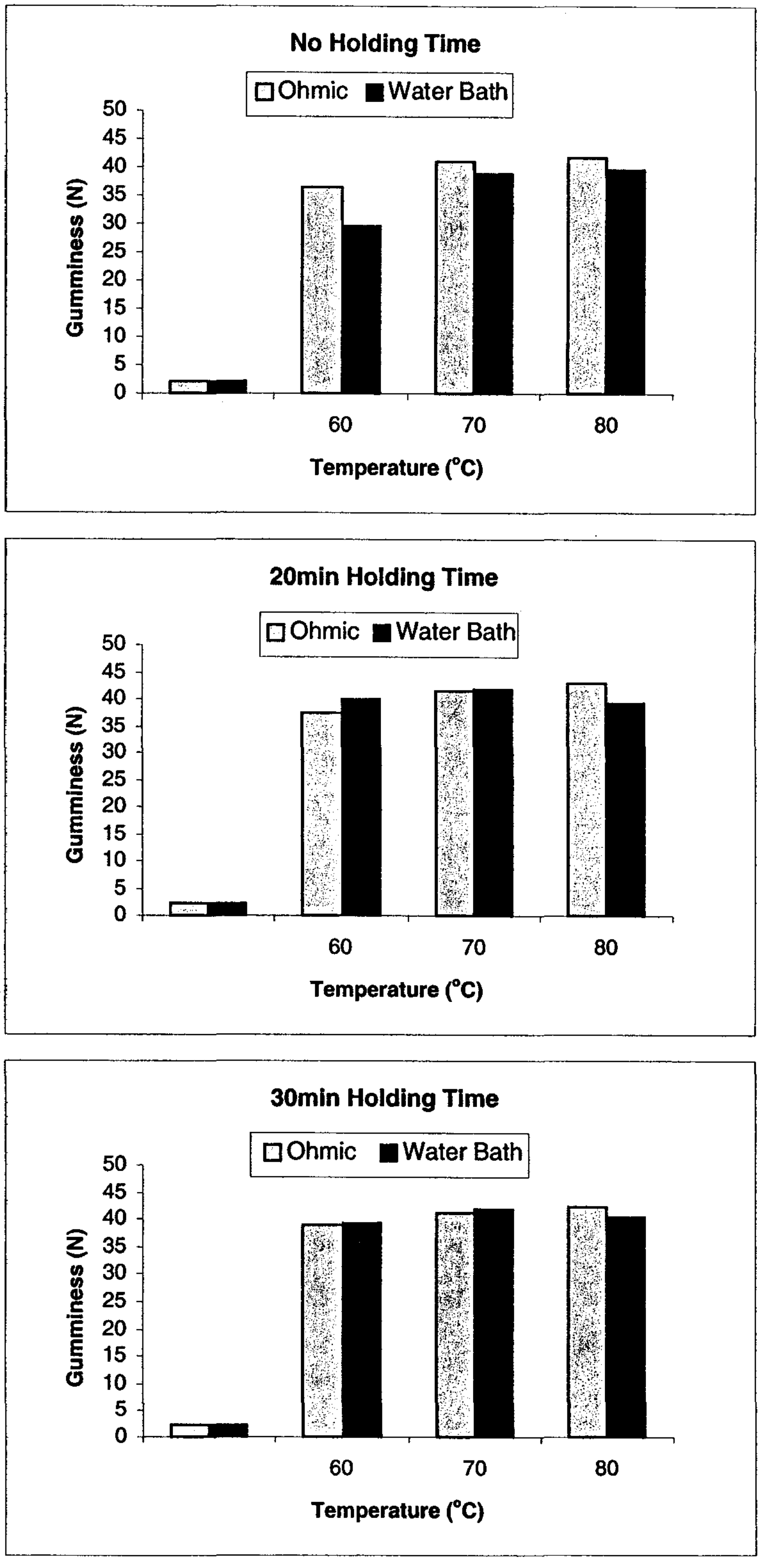


Figure 5.26 Gumminess of ham emulsions subjected to ohmic and conventional heating conditions

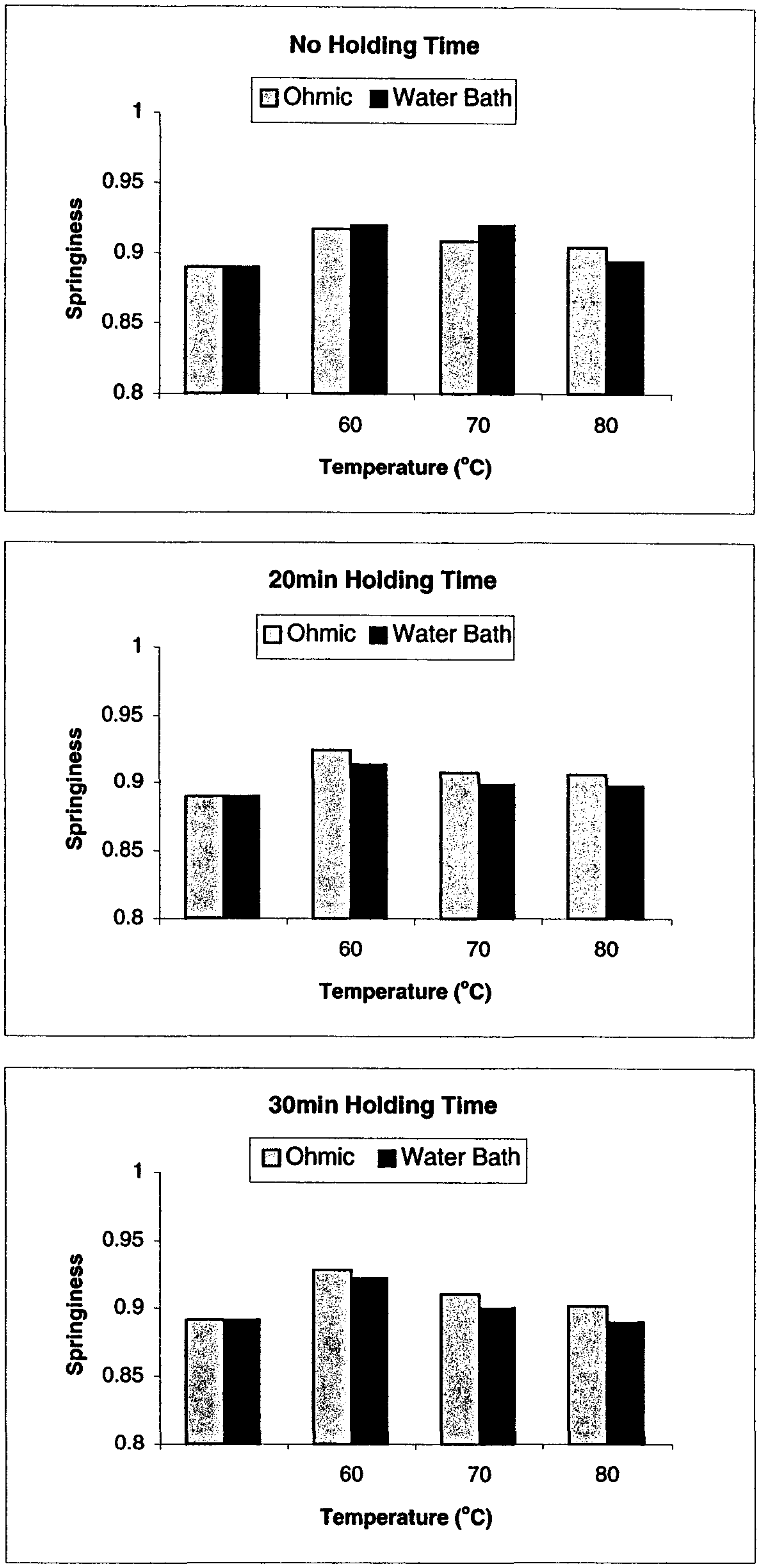


Figure 5.27 Springiness of ham emulsions subjected to ohmic and conventional heating conditions

Table 5.9 Mean Effects Table for texture parameters (N=20)

			Hardness (N)	Cohesiveness	Chewiness (N)	Gumminess (N)	Springiness
Temperature (°C)	60	OHM	51.29a	0.6735a	30.51a	33.86a	0.9132a
		CONV	54.37b	0.6621b	33.24a	35.98a	0.9238b
	70	OHM	58.75a	0.6554a	33.95a	37.96a	0.8984a
		CONV	64.51b	0.6267b	36.31a	40.43a	0.89687b
	80	OHM	59.82a	0.6457a	34.17a	38.33a	0.8949a
		CONV	61.68b	0.6261b	34.54a	38.61a	0.89503b
Holding Time (min)	0	OHM	56.50a	0.6562a	32.89a	36.57a	0.9014a
		CONV	58.80b	0.6354b	33.67a	37.23a	0.9059b
	20	OHM	56.84a	0.6628a	33.45a	37.27a	0.9028a
		CONV	61.45b	0.6494b	36.16a	39.81a	0.9087b
	30	OHM	56.31a	0.6556a	32.29a	36.31a	0.9024a
		CONV	60.32b	0.6301b	34.26a	37.99a	0.9011b

OHM: Ohmic heating; CONV: Conventional heating. Means for the different levels of a given variable not sharing the same letter within a column are significantly different by Duncan's multiple range at the 5% level.

Table 5.10 Analysis of variance of the factors influencing the texture values of ohmic and conventional processed fine ham emulsion

Factors	HAR	COH	CHW	GUM	SPN
Main Effects					
Tr	*	*	ns	ns	*
T	*	*	*	*	*
Ho	*	ns	ns	ns	ns
Interactions					
Tr x T	*	*	*	ns	ns
Tr x Ho	ns	ns	ns	ns	ns
T x Ho	*	ns	ns	ns	ns
Tr x T x Ho	*	ns	ns	ns	ns

Tr: treatment; T: temperature; Ho: holding time
HAR: hardness; COH: cohesiveness; CHW: chewiness; GUM: gumminess;
SPR: springiness
* significant at the 0.05 level
ns not significant at the 0.05 level

Yongsawatdigul and Park, 1996; Park *et al.*, 1998). This is because the rapid increase of temperature causes proteases to be inactivated before they could substantially hydrolyse myofibrillar proteins (de Alwis and fryer, 1990). Pacific whiting surimi gels heated slowly in a water bath exhibited poor gel quality, while the ohmically heated gels without holding at 55°C showed more than a twofold increase in shear stress and shear strain over conventionally heated gels. Degradation of myosin and actin was minimized by ohmic heating, resulting in a continuous network structure. (Park *et al.*, 1998).

The results of the analysis of variance presented in Table 5.10, showed that the treatment (ohmic vs. conventional) significantly influenced ($p<0.05$) the hardness, cohesivness and springiness. Temperature influenced all texture parameters. Holding time effect was not significant ($p>0.05$) with any of the testing conditions. Besides the main effects, most of the interactions do not reveal any critical differences ($p>0.05$).

5.4.2.4. Cooking loss, water holding capacity and water activity

Figures 5.28 to 5.30, and Tables 5.11 and 5.12 show the results of the cooking loss, water holding capacity and water activity of fine ham emulsion as influenced by ohmic and conventional heating conditions. Cooking loss was predominantly lower for samples subjected to ohmic heating conditions as compared to conventional heat treatment. Cooking losses increased with temperature and holding time. Water holding capacity was higher with the conventionally heated product than that subjected to ohmic heating.

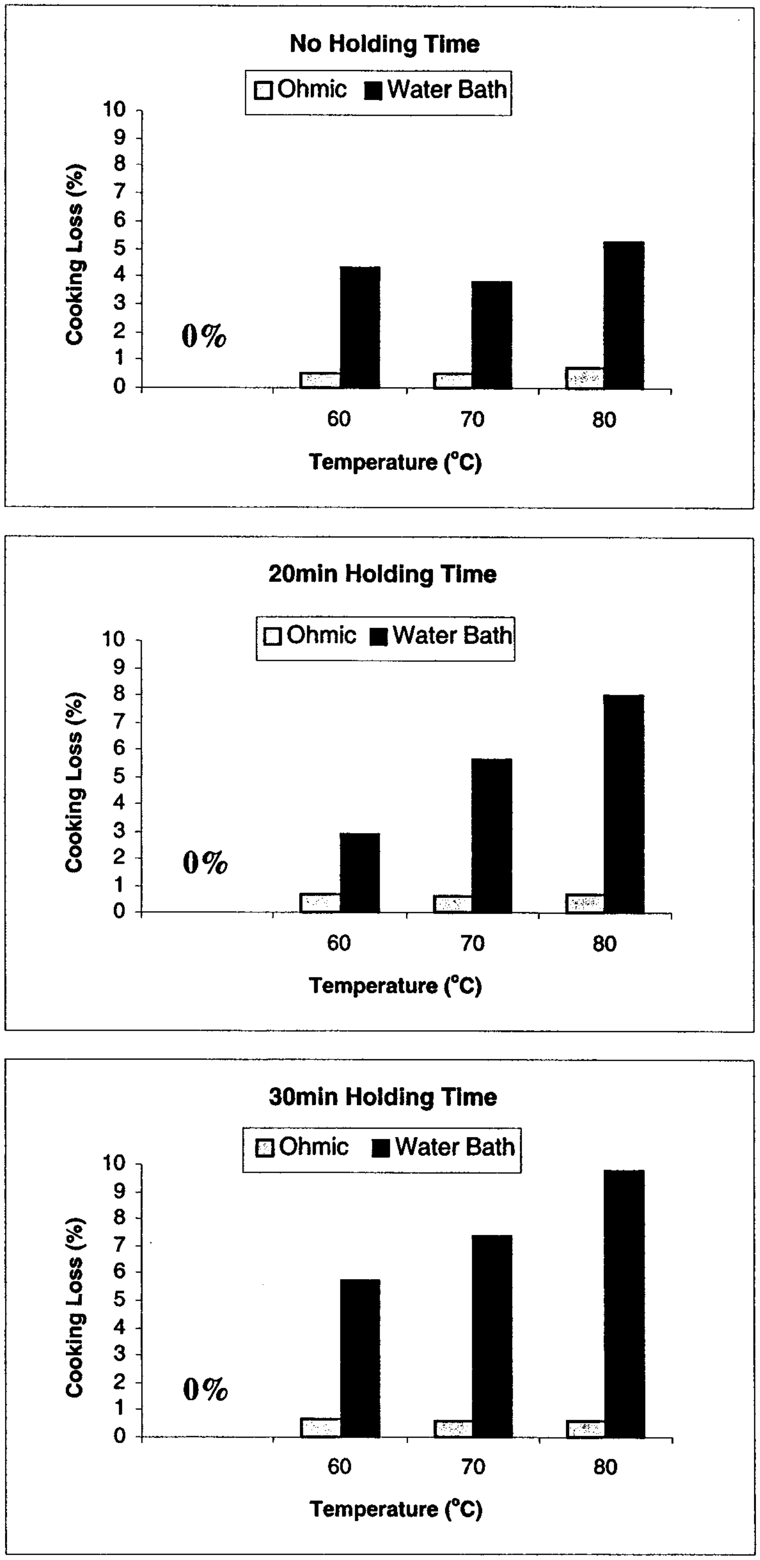


Figure 5.28 Cooking loss of ham emulsions subjected to ohmic and conventional heating conditions

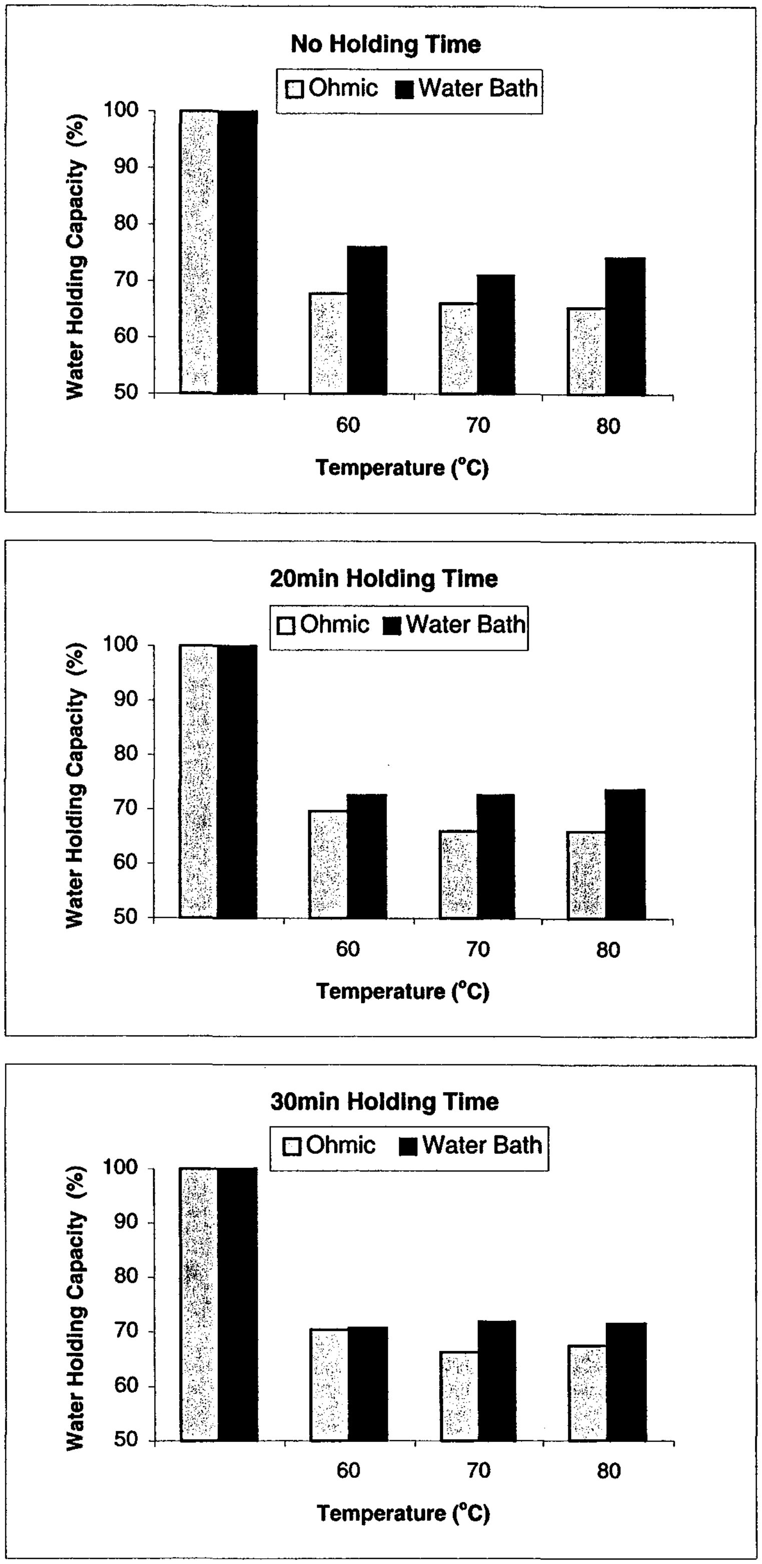


Figure 5.29 Water holding capacity of ham emulsions subjected to ohmic and conventional heating conditions

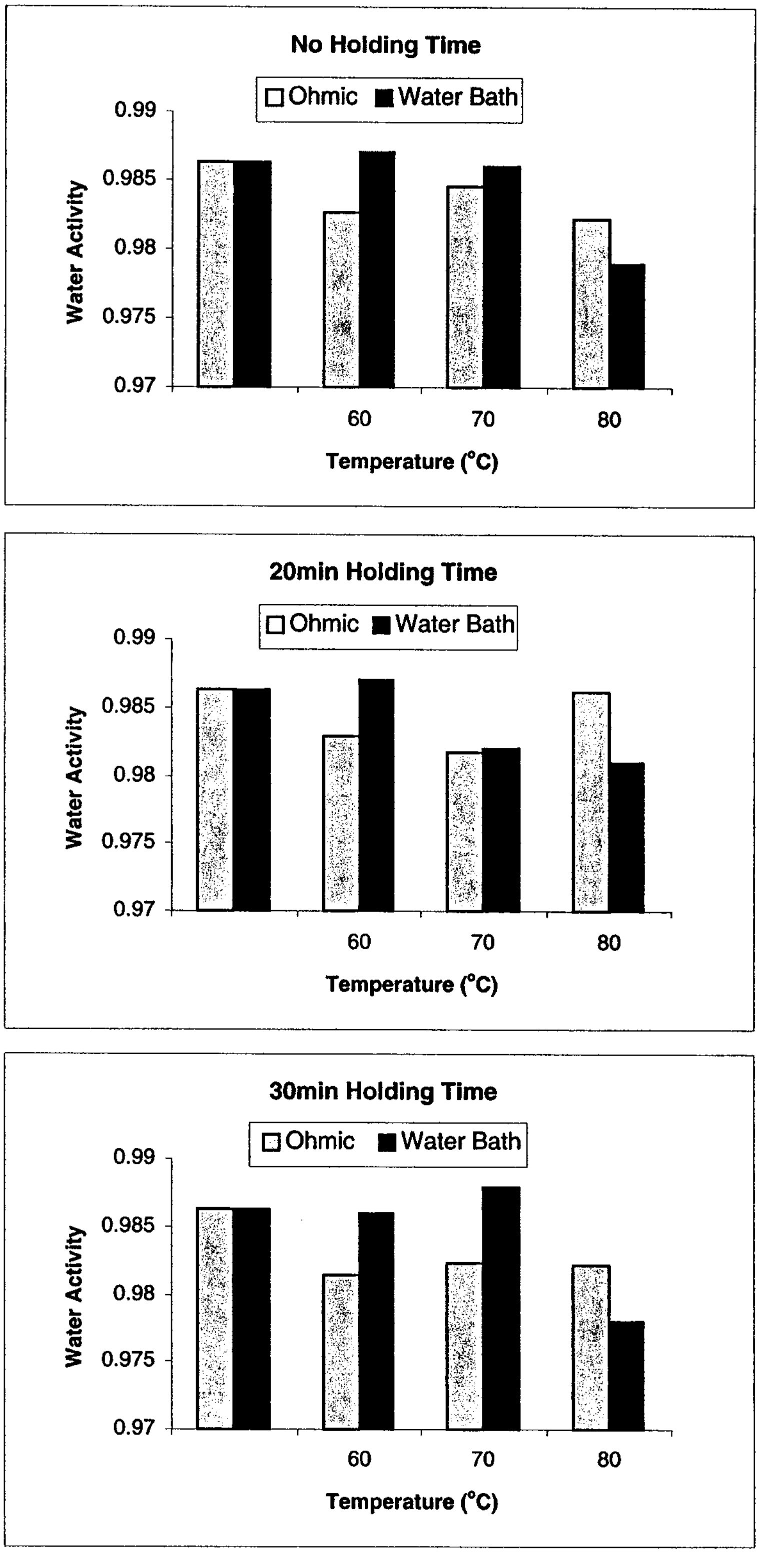


Figure 5.30 Water activity of ham emulsions subjected to ohmic and conventional heating conditions

Table 5.11 Mean effects table for cooking loss, water holding capacity and water activity

			Cooking Loss (%) (N=6)	**Water Holding Capacity (%) (N=6)**	**Water Activity (N=12)**
Temperature (°C)	60	OHM	0.5844a	69.68a	0.9813a
		CONV	5.5603b	70.79b	0.9881b
	70	OHM	0.5211a	66.33a	0.9815a
		CONV	7.7553b	72.93b	0.9858b
	80	OHM	0.6278a	64.28a	0.9831a
		CONV	8.3173b	73.79b	0.9847b
Holding Time (min)	0	OHM	0.7511a	66.67a	0.9820a
		CONV	6.2770b	73.52b	0.9858b
	20	OHM	0.4950a	67.39a	0.9822a
		CONV	7.4830b	73.16b	0.9883b
	30	OHM	0.4872a	66.23a	0.9817a
		CONV	7.8730b	70.84b	0.9846b

OHM: Ohmic heating; CONV: Conventional heating. Means for the different levels of a given variable not sharing the same letter within a column are significantly different by Duncan's multiple range at the 5% level.

Table 5.12 Analysis of variance of the factors influencing the cooking loss, water holding capacity and water activity values of ohmic and conventional processed fine ham emulsion

Factors	Cooking Loss	Water Holding Capacity	Water Activity
Main Effects			
Tr	*	*	*
T	ns	*	ns
Ho	ns	ns	*
Interactions			
Tr x T	ns	*	*
Tr x Ho	ns	*	*
T x Ho	ns	ns	*
Tr x T x Ho	ns	ns	ns

Tr: treatment; T: temperature; Ho: holding time
* significant at the 0.05 level
ns not significant at the 0.05 level

Although the differences were small, the water activity of test samples from conventional heating conditions were generally higher than those of ohmically heated samples.

The main effects and interactions for cooking loss, water holding capacity and water activity are summarized in Table 5.12. Cooking loss was significantly ($p<0.05$) affected by the treatment with conventional heating resulting larger losses. Holding time and temperature effects were not significant ($p>0.05$). Water holding capacity was significantly influenced ($p<0.05$) by temperature, come-up time, holding time and the interactions between temperature x come-up time, temperature x holding time, and come-up time x holding time. Water activity was influenced ($p<0.05$) by temperature, interaction of come-up time x holding time and temperature x come-up time x holding time.

5.5. CONCLUSIONS

Fine ham emulsions subjected to conventional and ohmic heating was evaluated at 60, 70 and 80°C with 3 different come up times (5, 10 & 20 min), and three holding time (0, 20 and 30 min; only 20 min holding time for when comparing ohmic vs. conventional heating). The color and texture parameters as well as cooking loss, water holding capacity and water activity of control and treated samples were evaluated.

Cooking temperature and come-up time significantly ($p<0.05$) influenced the color and texture of test samples subjected to ohmic heating conditions, higher temperatures, shorter come-up times and longer holding times showing lighter color, and softer texture Further, compared to the conventionally cooked product, ham emulsions cooked under ohmic heating conditions were lighter and more "pink or red" color, softer and chewier texture ($p<0.05$). The associated water holding capacity and cooking loss were also lower ($p<0.05$) in ohmic heated samples than in the conventionally cooked samples.

These results show that the rapid heating achieved under ohmic heating conditions provides some improvements in product quality in comparison to the conventional heating method. In addition, cooking time can be reduced by 75% (5 min vs. 20 min come-up; with no hold time) which could result in better production rate.

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