CHAPTER II

LITERATURE REVIEW

2.1 Ohmic heating process

Ohmic heating occurred when electric current passed through the material of electrical resistance, resulting in energy generation and caused temperature rise throughout its volume according to Ohm's law as in equations 2.1 and 2.2. The food itself served as an electrical resistance (or act as a conductor) of electricity (Figure 2.1), where the conductivity of the food would determine the current that flew between the electrodes. The food was internally heated due to its electrical resistances without involving any heating medium and heating transfer surface supporting a rapid heating rate. Moreover ohmic heating could provide uniform temperature distribution because both liquid and solid phases were heated simultaneously (Parrot, 1992; Sastry, 1992). The basic relationship for the energy-generation rate of a food was shown in equation 2.3 (Sastry and Barach, 2000).

$$V = IR \qquad \text{.......................(2.1)}$$

$$P = VI = I^2R \qquad \text{.......................(2.2)}$$

$$Q = |\nabla V|^2\sigma \qquad \text{.......................(2.3)}$$

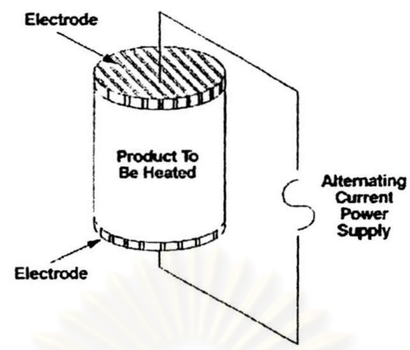


Figure2.1 Principle of Ohmic heating

2.2 Electrical Conductivity

Most foods contained ionic substances such as salts and acids which acted as electrolytes, so that an electric current could pass through the food and generated heat inside it. Electrical conductivity (σ), in Siemens per meter, was measured with a conductivity cell filled with product heated to various temperatures. The resistance between the two electrodes at each end of the cell was calculated from the measured voltage and current data. The electrical conductivity of the sample was calculated from the resistance and the cell constant as shown in equation 2.4 (Palaniappan and Sastry, 1991a,b).

$$\sigma = (1/R)(L/A) = K_c(1/R) \qquad \text{..........................(2.4)}$$

2.3 Factors affecting the ohmic heating process

To design a food formulation using the advantages of electrical heating required an understanding of the process and the factors affecting product sterility and quality. The process was controlled by the heat generation rate, which was governed by a number of factors. The most important of which was the electrical conductivity of the food material.

However, temperature was also affected by the way food flew through the heater and, thus, the residence time within the heating unit. However, this study considered only a static situation so that the literature review would cover those for static condition.

2.3.1 Electrical conductivity of foods

The critical property influencing the rate of ohmic heating was the electrical conductivities of food which depended on a number of factors, including temperature, ionic constituents, material microstructure and electric field strength (deAlwis and Fryer, 1992; Sastry and Barach, 2000; Halden, deAlwis, and Fryer, 1990).

2.3.1.1 Temperature

The temperature dependency of electrical conductivity for variety of foods has been reported extensively (Plaichoom, 2002; Marcotte, Trigui, and Ramaswamy, 2000; Kanchanakitsakul, 1999; Yongsawatdigul, Park, and Kolbe, 1995; Wang and Sastry,1993; deAlwis and Fryer, 1992; Palaniappan and Sastry, 1991a,b; Halden *et al.*,1990). The electrical conductivity of foods typically increased linearly with temperature. The relationship between electrical conductivity and temperature could be expressed as equation 2.5.

$$\sigma_T = \sigma_{ref}\,[1 + m\,(T - T_{ref})] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

The temperature coefficient indicated the increase in conductivity at high temperature which was likely due to the increasing in ionic mobility at high temperature (Palaniappan and Sastry, 1991a,b).

The linear relationship between the σ and temperature was found in a variety of liquid foods such as pineapple drinking yoghurt (Plaichoom, 2002), hydrocolloid solutions (Marcotte *et al.*, 2000), orange and tomato juices (Palaniappan and Sastry, 1991b). It was also found in raw potato at high voltage gradient (Palaniappan and Sastry, 1991a), blanched vegetables, i.e. blanched potato, carrot, and white radish (Kanchanakitsakul, 1999), blanched mushroom (Halden *et al.*, 1990), and some animal samples, i.e. surimi (Yongsawatdigul *et al.*, 1995), lamb (deAlwis and Fryer, 1992), chicken and beef (Palaniappan and Sastry, 1991a). For raw vegetable samples such as potato (Kanchanakitsakul, 1999; Palaniappan and Sastry, 1991a; Halden *et al.*, 1990), beet root (Halden *et al.*,1990), carrot and yam (Palaniappan and Sastry, 1991a), it was found that the σ increased slightly with temperature up to approximate 60°C, at which cellular breakdown occurred, then the curve underwent a steep increase under relatively low voltage gradient.

For a mixture of liquid with particles, the linear relationships were found in blanched potato, carrot, and white radish in salt solutions with various solid concentrations (Kanchanakitsakul, 1999), and raw potato cubes in 0.05 and 0.1M sodium phosphate solution (Palaniappan and Sastry, 1991c) but non-linear curve (similar to that obtained from raw potato at low voltage gradient) was found in the mixture of raw potato of high volume fraction in dilute (0.025M) sodium phosphate solution (Palaniappan and Sastry, 1991c).

For most ohmic heating applications, a linear σ-T relation would appear because most solid foods were likely to be precooked or thermally pretreated for enzyme inactivation before ohmic heating (deAlwis and Fryer 1992). The temperature dependence of electrical conductivity for some selected foods had been expressed as equations shown in Table 2.1. Some studies had also reported the relationship between conductivity, temperature and compositions as shown in Table 2.2.

Table 2.1 The temperature dependence electrical conductivity equations of food materials

Materials	Temperature range (°C)	Voltage Gradient (V/cm)	Electrical conductivity equations	R^2	Reference
Potato, raw	25-120	60	$\sigma = 0.32\,[1+0.035(T-25)]$	0.94	Palaniappan and Sastry (1991a)
Potato, raw	30-100	25	$\sigma = -3.06+0.0982T$	0.98	Wang and Sastry (1993)
Potato, raw	n.r.	n.r.	$\sigma = 0.047-2.5\times10^{-3}(T^{*}-273)+4.7\times10^{-5}(T^{*}-273)^2$	n.r.	deAlwis and Fryer (1990)
Potato, blanched	25-125	30	$\sigma = 0.0553+0.0019T$	0.99	Kanchanakitsakul (1999)
Carrot, raw	25-120	60	$\sigma = 0.13\,[1+0.107(T-25)]$	0.96	Palaniappan and Sastry (1991a)
Carrot, blanched	25-125	30	$\sigma = 0.0207 + 0.0007T$	0.99	Kanchanakitsakul (1999)
Yam, raw	25-120	60	$\sigma = 0.11\,[1+0.097(T-25)]$	0.98	Palaniappan and Sastry (1991a)
White radish, blanched	25-125	30	$\sigma = 0.0487+0.0021T$	0.99	Kanchanakitsakul (1999)
Chicken, raw	25-120	60	$\sigma = 0.37\,[1+0.019(T-25)]$	0.9	Palaniappan and Sastry (1991a)
Beef, raw	25-120	60	$\sigma = 0.44\,[1+0.016(T-25)]$	0.96	Palaniappan and Sastry (1991a)
Lamb, raw	n.r.	n.r.	$\sigma = 0.0344+6.8\times10^{-3}(T-273)^{*}$	n.r.	deAlwis and Fryer (1990)
0.01M NaCl	25-125	30	$\sigma = 0.1195+0.0039T$	0.99	Kanchanakitsakul (1999)

n.r. = not reported

* Temperature in K

Table 2.2 The temperature and composition dependence electrical conductivity equations of food materials

Materials	Temperature range (°C)	Voltage Gradient (v/cm)	Electrical conductivity equations	R^2	Reference
Surimi, Pacific Whiting	up to 90	3.3-13.3	σ = 0.1168+0.0083 T-2.5115 SaT+ 0.0385 M_wSa+0.0229 TSa+0.0282 Sa^2	0.99	Yongsawatdikul et al. (1995)
Orange juice	25-85	42.4	σ = 0.567 [1+0.242(T-25)]-0.306 S	0.98	Palaniappan and Sastry (1991b)
Tomato juice	25-85	42.4	σ = 0.863 [1+0.174 (T-25)]-0.101 S	0.97	Palaniappan and Sastry (1991b)
Pineapple drinking yoghurt		20	σ = 0.1366+0.012 T-0.0011 S	0.98	Plaichoom (2002)
		30	σ = 0.0999+0.0138T +00.0033S	0.96	Plaichoom (2002)
Carrageenan solution 1.7%	20-80	7.25	σ = 1.08+0.014 T+0.034 SaT	0.99	Marcotte *et al.* (2000)
Xanthan Solution 2%	20-80	7.25	σ = 1.15+0.013 T+0.033 SaT	0.99	Marcotte *et al.* (2000)
Pectin solution 2.5%	20-80	7.25	σ = 1.04+0.0085 T+0.034 SaT	0.99	Marcotte *et al.* (2000)
Thermoflo' starch solution 4.3%	20-80	7.25	σ = 1.01+0.0016 T+0.0417 SaT	0.99	Marcotte *et al.* (2000)

2.3.1.2 Ionic constituents

Most foods contained a moderate percentage of free water containing dissolved ionic substances such as salts and acids which acted as electrolytes, so that an electric current could be made to pass through the food and generate heat inside it. The presence of ionic constituents obviously had pronounced effects on electrical conductivity. Several researchers had reported that electrical conductivity increased with salt content on hydrocolloid solutions (Marcotte *et al.*, 2000) and surimi (Yongsawatdigul *et al.*, 1995). Soaking solid foods in salt solution or leaching in water may alter its ionic concentration. Palaniappan and Sastry (1991a) found that conductivities of vegetable samples (potato, carrot, and yam) were increased by soaking in 0.2-0.8% salt solution, while the conductivities were reduced due to leaching of electrolytes when soaking in water (Table 2.3). Wang and Sastry (1993) determined the effect of salt diffusion (1-3%) by either normal soaking or vacuum infusion methods on electrical conductivity and heating rate of potato and found that samples soaked in a higher concentration brine had a higher electrical conductivity and heating rate for both soaking methods. More electrolytes in solid foodstuff would allow more current flow and resulted in higher heating rate (Palaniappan and Sastry, 1991c; Wang and Sastry, 1993). The σ-T curves of potato as affected by salt concentration in vacuum infusion process were shown in Figure 2.2.

The presence of non-ionic constituents, such as bone, oil and fat, syrup, and ice, as a natural insulator would affect the electrical conductivity and the current flow may not be enough to generate sufficient heat (Zoltai and Swearingen, 1996). Halden *et al.* (1990) compared the heating of a slice of pork meat and pork fat in brine and found that pork fat was heated slower with the globules of oil appeared on the surface of brine.

Table 2.3 Parameters of the electrical conductivity equations* of vegetable soaked in various solutions

Material	Treatment	σ_{25}** (S/m)	m	R^2
Potato	Raw	0.32	0.035	0.94
	Water	0.25	0.030	0.96
	0.2% NaCl	0.37	0.028	0.98
	0.4% NaCl	0.36	0.033	0.88
	0.8% NaCl	0.43	0.027	0.97
Carrot	Raw	0.13	0.107	0.96
	Water	0.12	0.078	0.98
	0.2% NaCl	0.29	0.044	0.92
	0.4% NaCl	0.31	0.044	0.96
	0.8% NaCl	0.25	0.062	0.98
Yam	Raw	0.11	0.094	0.98
	Water	0.09	0.079	0.98
	0.2% NaCl	0.42	0.021	0.85
	0.4% NaCl	0.35	0.032	0.94
	0.8% NaCl	0.35	0.034	0.96

Source: Palaniappan and Sastry (1991a)
*equation 2.5
**$\sigma_{25} = \sigma$ at 25°C

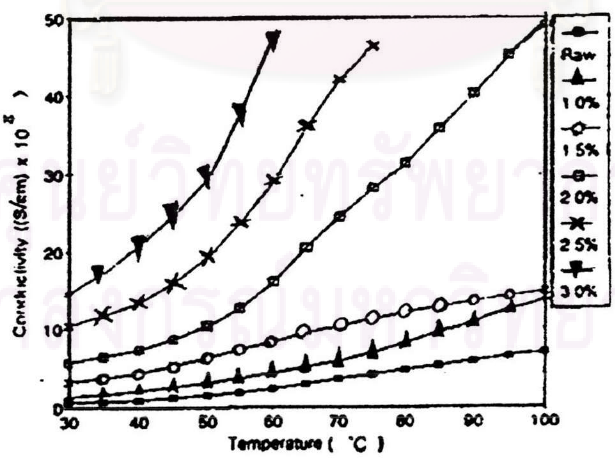


Figure 2.2 Electrical conductivity curves of raw and vacuum diffused potato in 1.0, 1.5, 2.0, 2.5, 3.0 % salt solution.
Source: Wang and Sastry (1993)

2.3.1.3 Food structure

The solid foods may have different electrical conductivities in nature. However, changes in food structure during processing e.g. starch gelatinization or cell lysis could affect the electrical conductivity by changing the ionic concentration or ionic mobility. The slope of the σ-T curve of a potato slice increased after 75-80°C due to starch gelatinization (Halden *et al.*, 1990) while those of carrot increased after 60°C due to cell wall breakdown (Palaniappan and Sastry, 1991a).

Large variations of σ-T and temperature-time curves of solid samples between trials due to non-homogeneous of food structures had been mentioned by many researchers (Palaniappan and Sastry, 1991a; Wang and Sastry, 1997b; Lima, Heskitt, and Sastry, 1999; Lima and Sastry, 1999; Fu and Hsieh, 1999). Evidence was shown in Figure 2.3 by Lima *et al.* (1999) who found the variations in electrical conductivities among six trials under identical conditions of raw turnip tissue pieces bored perpendicular to vascular tissues. Structural variations throughout the cross section of turnip due to the distribution of vascular tissue were thought to cause these differences.

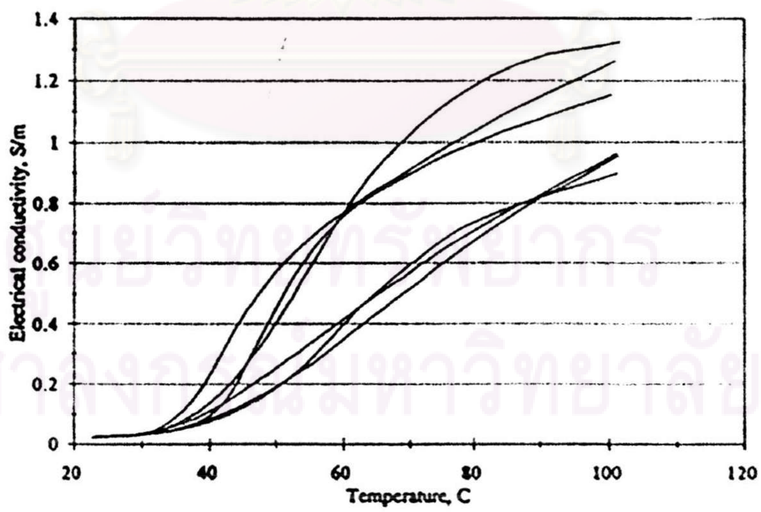


Figure 2.3 Variations in electrical conductivities of turnip tissues among six trials of experiment under identical condition
Source: Lima *et al.* (1999)

2.3.1.4 Voltage gradient

The electrical conductivities of fruit and vegetables were found to increase with increasing voltage gradient (Halden *et al.*, 1990, deAlwis and Fryer 1990). High applied voltage gradient enhanced cell fluids motion within plant cells and ruptured cell membranes, resulting in release of cell fluids. Palaniappan and Sastry (1991a) found that σ-T curves of carrot changed from non-linear at low voltage gradient to be linear at relatively high voltage gradient, and the σ values increased with increasing applied voltage (Figure 2.4) which was possibly due to electro-osmotic effect. On the other hand, different results were obtained in animal tissue. Yongsawatdigul *et al.* (1995) reported that the voltage gradients (3.3, 6.7, and 13.3 V/cm) had no effect on electrical conductivity of PacificWhiting surimi. It was explained that the voltage gradients were unlikely to enhance the cell fluid motion within a finely comminute and homogeneous material of surimi as those reported in plant cells.

For liquid foods, the voltages may influence electrical conductivity differently among types of foods. For pineapple-drinking yoghurt, Plaichoom (2002) found that the electrical conductivity increased as the voltage gradients increased from 10 to 40 V/cm. This may possibly due to electro-osmosis effect of pineapple in the yoghurt, resulted in release of more ions. For orange juice, Palaniappan and Sastry (1991b) found that the σ-T curves were not directly affected by the voltage gradients but the decrease in transition temperature at the end of heating with increasing voltage gradient was observed (Figure 2.5). The transition temperature was the point at which a sudden drop in electrical conductivity occurred during heating up to 80-85°C due to the presence of small hydrogen gas bubbles near the electrodes. The decrease in transition temperature with increasing voltage gradients indicated the acceleration of hydrogen gas production reaction as the orange juice contained some weak acids which could be subjected to electrolytic hydrogen bubble formation (Palaniappan and Sastry, 1991b).

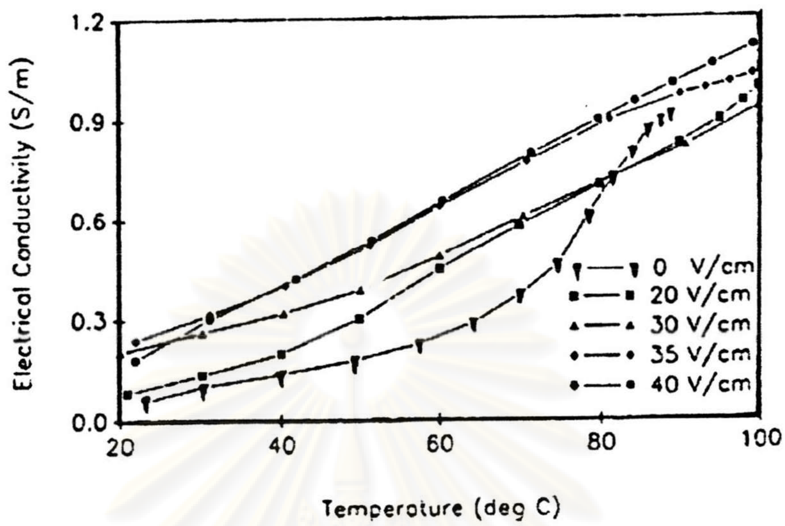


Figure 2.4 Electrical conductivity curves for carrot (parallel to stem axis) subjected to various voltage gradients
Source: Palaniappan and Sastry (1991a)

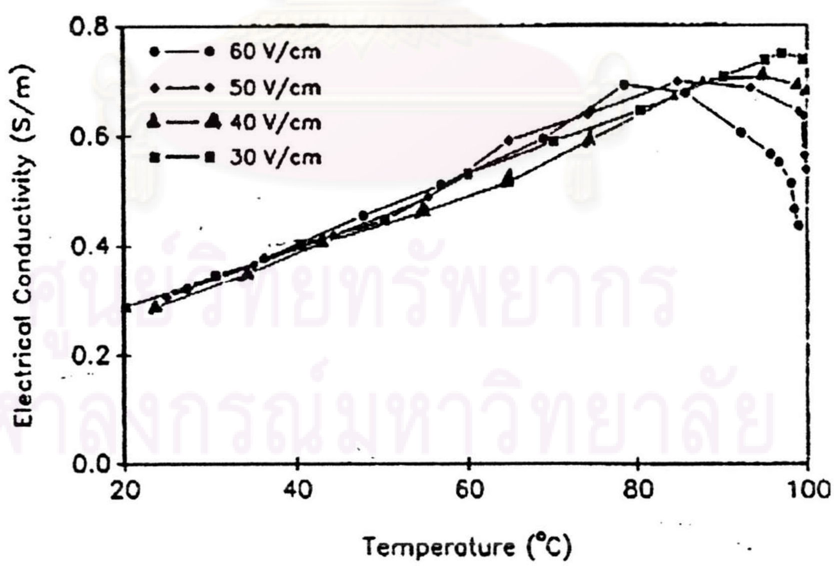


Figure 2.5 Effect of voltage gradients on electrical conductivity of orange juice
Source: Palaniappan and Sastry (1991b)

2.3.1.5 pH

The effect of acidity was scarcely documented in the literature. Skudder and Biss (1987) reported that acids could increase the ionic content that rendered the food electrically more conductive. However, the effect of added citric acid on electrical conductivities of selected hydrocolloid solutions at normal and modified pH was studied by Marcotte *et al.,* (2000). The pH was varied from the normal pH of carrageenan and starch from 8.8 to 6.5-6.8; xanthan from 6.3 to 2.8; and pectin from 3.5 to 2.8. The effects of citric acid addition on both electrical conductivities and heating profiles were found to be small. It was suggested that citric acid was an organic acid that was not strongly dissociated. This was not sufficient to show major differences in electrical conductivities and heating profiles even though large differences were determined between normal and modified pH.

2.3.2 Electric field strength or current density

Current density was the current divided by the cross-sectional area of the electrode. Since the current related directly to the voltage (equation 2.1), the current density was corresponded to the voltage gradient or electric field strength which was voltage applied per length of the ohmic cell. Increasing electric field strength would directly increase the power of the system (equation 2.2) and result in higher heat generation (equation 2.3). (deAlwis and Fryer, 1992; Parrot, 1992; Sastry and Palaniappan, 1992b; Kim *et al.*, 1996)

2.3.3 Frequency and wave form

Most ohmic heating research to date had been done at frequencies of 50 and 60 Hz. (standard frequency for alternating current in the United Kingdom and United States of America). Several studies had demonstrated the effect of frequency and wave shape of alternating current on ohmic heating of foods.

Studies of effect of frequency on electrical conductivity had been conducted in both low frequency (4-60 Hz., Lima *et al.,* 1999; Lima and Sastry, 1999) and high frequency (50 Hz.–10 kHz., Imai *et al.*, 1995; Park *et al.*, 1995). It was found that lower frequency affected the electrical conductivity and heating rate by changing the cell membrane structure due to electroporation phenomena. Imai *et al.* (1995) found that, the heating rate of Japanese white radish increased as frequency decreased while Lima *et al.* (1999) found the heating rate of turnip tissue increased with decreasing frequency. In contrast, different result was reported by Park *et al.* (1995) that the heating rate of fish minced meat 'kamaboko' from Alaska Pollack had higher heating rate at higher frequency due to the dielectric loss.

Effect of wave forms of alternating current on electrical conductivity of some vegetables was also investigated. A comparison of wave forms showed that square wave had significantly low σ compared to sine and sawtooth waves but no significant difference was found on the heating rate of raw turnip subjected to ohmic heating to 100°C (Lima *et al.*, 1999).

2.3.4 Fluid viscosity

In conventional heating, increasing the viscosity of fluid would retard the heating of fluid due to low heat transfer coefficient (Marcotte, Ramaswamy, and Piette, 1998). In ohmic heating, the effect of thermal behavior of hydrocolloid solutions with different concentrations on heating rate was investigated by Marcotte *et al.* (1998) and found that heating was more efficient as the concentrations of hydrocolloid solutions increased. The higher electrical conductivity associated with higher concentration of hydrocolloids appeared to dictate the heating rate and override the negative effect of increased viscosity. The study of Khalaf and Sastry (1996) was conducted to determine the effect of viscosity on temperature of both solid and liquid in the mixture by minimizing the electrical conductivity effect. The CMC solutions of the same electrical conductivity but different viscosities with the same amount of particles were compared in three ohmic heating systems: static, a vibrating unit, and continuous system. The results showed that the heating rates of fluid and particle were not significantly affected by fluid viscosity under static condition, because of extremely limited fluid flow. However, with sufficient agitation, as in vibrating unit or continuous flow ohmic heater, the rate of heating increased with fluid viscosity. Enhanced heating of the fluid phase for the viscous case, resulted in an increase in temperature difference between the fluid and solids which counteracted the effect of low heat transfer coefficient.

2.3.5 Particle size

The size of suspended solids had been shown to affect electrical conductivity. Studies using various size of carrot solids suspended in sodium phosphate solution had indicated that electrical conductivity increased with decreasing particle size (Palaniappan and Sastry, 1991b). This was because smaller particles reduced drag of ionic movement or possibly released more intracellular fluids due to the higher in surface area per volume ratio. The same result was also found when varying size of non-conductive polystyrene sphere in sodium phosphate solution. So it was suggested that the particle size dependence was likely due to structural rather than chemical effects.

Sastry (1993) studied the effect of size for cylindrical potato particle in sodium phosphate at the aspect ratio (radius/length) of 0.093 and 0.386 and found that fluid temperature increased as aspect ratio decreased. This could be explained that the low-aspect ratio particle had greater surface area per unit volume so that the interphase heat transfer was more rapid.

2.3.6 Particle shape and orientation

A solid immersed in liquid could either be heated faster or slower than the liquid depending on both solid and liquid electrical conductivities and the orientation of the particles in the electric field. de Alwis, Halden, and Fryer (1989) studied the effect of orientation on heating rate by placing a 40x75x30 mm potato piece (σ = 0.04 S/m) in a salt solution (σ = 0.58 S/m) parallel and perpendicular to the electric field. It was found that the solid was heated faster than the liquid if placed perpendicular, whereas the liquid was heated faster than the solid in parallel orientation (Figure 2.6). In the case that particle was oriented across the current, it tended to 'block' the current, and formed a large part of the overall resistance. Under this conditions, the current had relatively few alternate paths, and the particle interior heated faster than the fluid. If, on the other hand, the particle was oriented parallel to the current, its resistance formed only a small part of overall resistance, a number of parallel conduction paths became available, and the particle lagged behind the fluid. For cubic and spherical particles, the effects were relatively small.

Sastry and Palaniappan (1992b) found that for a cubic particle, the heating rate of a potato cube of 10x10x10 mm in 0.1M sodium phosphate solution was not affected by orientation, either parallel or 45° angle to the electric field.

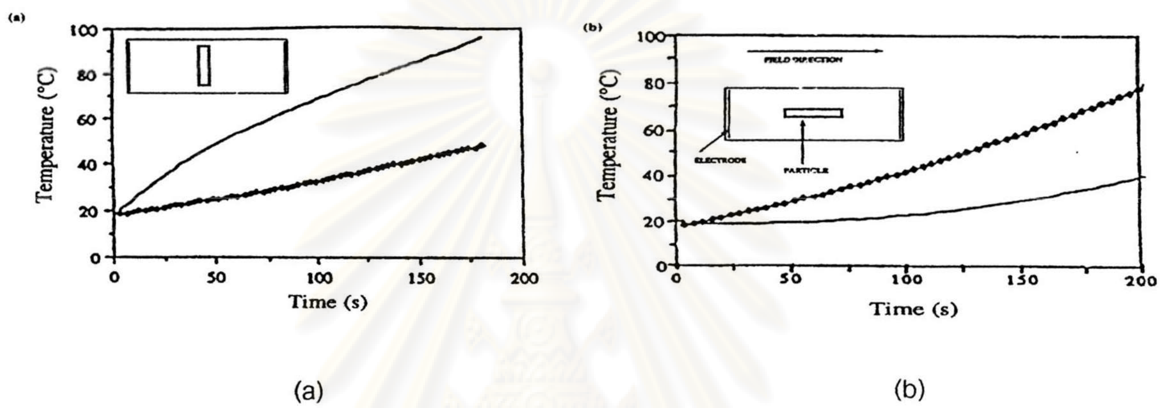


Figure 2.6 Temperature of liquid (▪-▪) and particle(-------) according to orientation of electric field.(a) perpendicular (b) parallel
Source: de Alwis *et al.* (1989)

2.3.7 Particle concentration

In solid-liquid mixtures, increasing particle concentration would result in lower the electrical conductivities and heating rate. Plaichoom (2002) found that the electrical conductivities as well as heating profiles of pineapple-drinking yoghurt decreased as the concentration of 1cm pineapple cubes increased in the range of 0-20 % during pasteurized to 80°C. Kanchanakitsakul (1999) found that increasing the volume fractions of vegetable cubes from 0.2 to 0.6 (carrot, potato and white radish) in 0.1M salt solution decreased the effective electrical conductivities of the mixture in all combinations. Sastry and Palaniappan (1992a) found that the particles may be heated faster or slower than the liquid depending on the concentration of the solid particles in the mixture. Varying the particle concentration of potato (0.062 S/m) in 0.1M sodium phosphate solution (0.189 S/m) as: two particles of 15x15 mm; 20 and 30 particles of 8x8 mm corresponding to 0.23 and 0.345 volume fraction, it was found that as solid volume fraction increased, the particle temperature tended to increase relative to that of fluid (Figure 2.7). In the system containing two particles, the particles lagged behind that of the fluid. At volume fraction of 0.23, the particles lagged behind initially but eventually caught up the liquid temperature while the particle lagged initially but soon exceeded those of the fluid at volume fraction of 0.345. These were because as the solid concentration increased, the parallel conduction paths through the fluid were more restricted, forcing a greater proportion of the total current to flow through the particles. This resulted in higher generation rates within the particles and consequently a greater relative heating rate. Based on their work, it appeared that if a particle's electrical resistance within a circuit was a significant component of the overall resistance, the particle would likely heat faster than the fluid, even when fluid conductivity significantly exceeded that of particle. On the other hand, if the particle represented only a small part of the overall circuit resistance, significantly wide parallel conduction paths to the current would result in thermally lag of fluid (Sastry and Palaniappan, 1992a).

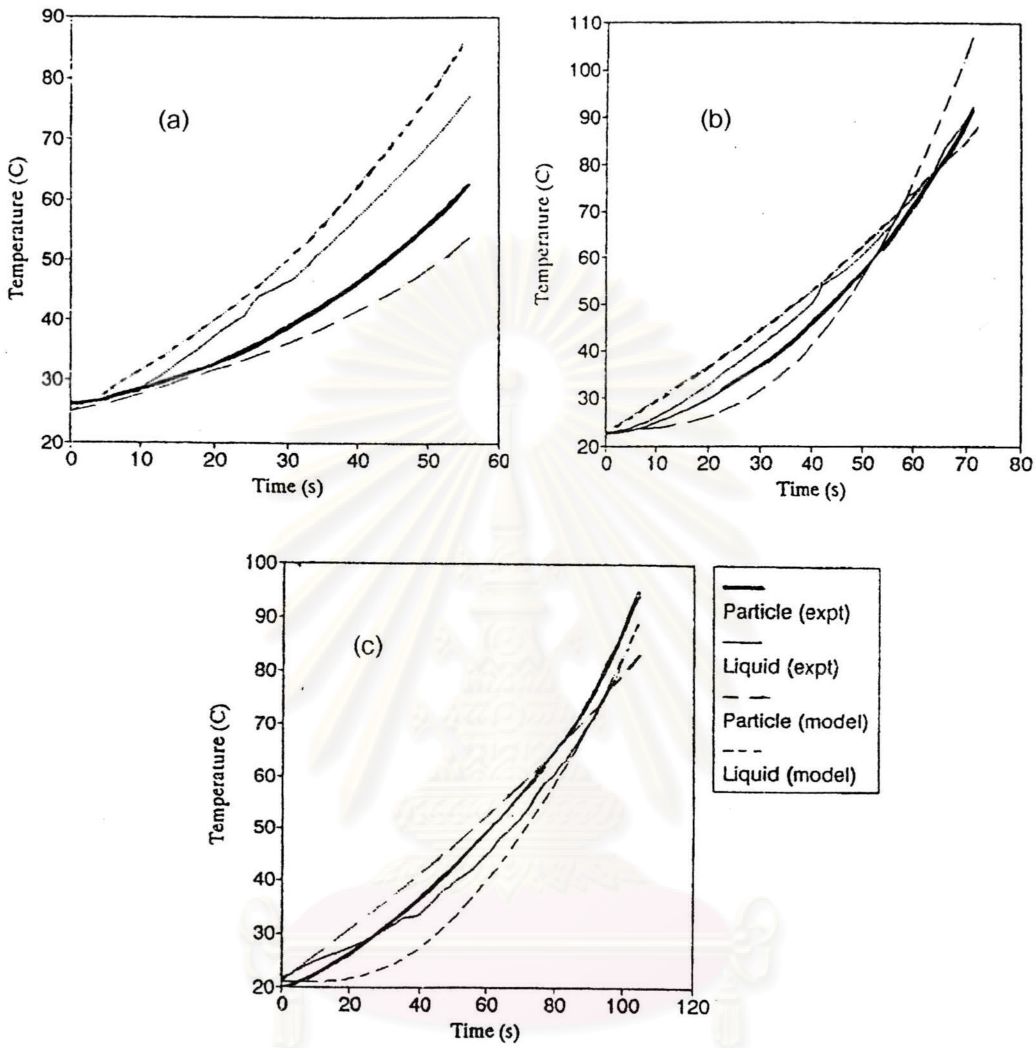


Figure 2.7 Ohmic heating for a suspension of potato particles in sodium phosphate solution (a) two particles; (b) twenty particles (vf = 0.23); (c) thirty particles (vf = 0.345)
Source: Sastry and Palaniappan (1992a)

2.3.8 Thermal properties of the food

In ohmic heating, passing the alternate current caused the internal energy generation within food materials (equation 2.3). The temperature rise due to volume-based energy generation or inherent heating rate, G, was calculated from equation 2.6 and expressed in equation 2.7 (Fryer *et al.*, 1993; Sastry and Palaniappan, 1992c)

$$Q = \sigma|\nabla V|^2 = \rho C_p \frac{dT}{dt} \qquad \text{.....................(2.6)}$$

$$G = \frac{dT}{dt} = \frac{Q}{\rho C_p} = \frac{\sigma|\nabla V|^2}{\rho C_p} \qquad \text{.....................(2.7)}$$

High heat generation would not necessary lead to rapid temperature increase if the food had a high thermal capacity (ρC_p). It was also noted that even if both solid and liquid had the same electrical conductivity, the two phases would still heat at different rates if their thermal capacities were different. In practice, heat transfer throughout the food materials by thermal conduction would also happen, so that the heating rate at any point in a material would be coupled with inherent heating rate of the material due to internal heat generation and the thermal conduction heat transfer as shown in equation 2.8 (Zhang and Fryer, 1993).

$$\frac{dT}{dt} = G + \frac{\nabla(k\nabla T)}{\rho C_p} \qquad \text{.....................(2.8)}$$

Thus, the thermal properties of food that may affect temperature distribution included the specific heat and thermal conductivity of food materials.

2.3.8.1 Specific heat

The specific heat of a material, C_p, was the amount of heat required to increase the temperature of a unit mass by one degree. It indicated how much heat was required to change the temperature of a material. Materials whose specific heat was not experimentally determined could be estimated from empirical equations. A strong linear correlation between specific heat and water content was reported (Sweat, 1986). One of the most common equations was developed by Siebel (Toledo, 1991) as given by equation 2.9, for value above freezing:

$$C_p = 837.36 + 33.48\, M_w \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.9)$$

The specific heat increased linearly with both moisture content and temperature. Rice, Selman, and Abdul-Rezzak (1988) investigated the effect of temperature on thermal properties of potatoes and found that the C_p significantly increased by 50% for a 50°C change in temperature, e.g. 2735 and 4015 J/kg°C at 40 and 90 °C, whereas the density slightly decreased from 1.127 to 1.103 g/ml at temperature range of 20 to 90 °C. From their data, a correlated equation 2.10 (R^2 = 0.98) was shown as follows:

$$C_p = -8239.5 + 25.9T + 130.9\, M_w \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.10)$$

Apart from potato, data for other food materials related in this study was limited.

2.4. Ohmic heating of liquid-particle mixture in static heater

Ohmic heating offered the possibility of rapid heating solid-liquid mixtures on a commercial scale. To understand what happened during heating, it was necessary to construct a model for the process both for designing the process and to ensure product and process safety. Fryer *et al.* (1993) suggested that different types of model were needed. Simple model relating power and temperature could describe a process as a basis for control and more complex model could be used to study the local thermal and electric fields around individual parts of the system.

The static heater was particularly important because it could approximate the geometry of the continuous heater and clearly demonstrated the effect of operational variables on heating rates of liquid and particles. It was also a useful device for verification of mathematical models.

2.4.1 Effective electrical conductivity

In solid-liquid mixtures, the effective or overall electrical conductivity was the key in determining the power consumption and mean heating rate of the process. The effective electrical conductivity was determined from the distribution of electrical conductivity in the system. Particles would be dispersed randomly in a fluid and would respond differently to an applied electric field. The form of response depended strongly on the electrical conductivity of each phase, particle size, shape and orientation to the electric field (Palaniappan and Sastry, 1991a; Sastry and Palaniappan, 1992c; Fryer *et al.*, 1993). In order to predict the heating effect of an ohmic heating system, the voltage distribution in the heated material had to be determined by solving the Laplace's equation (equation 2.11) with appropriate boundary conditions.

$$\nabla(\sigma \nabla V) = 0 \qquad \text{.........................(2.11)}$$

The voltage field was subjected to two types of variation; large scale due to the medium being heated along the heater length and smaller scale due to differences in phase conductivities. Large scale effect resulted in the major temperature changes over the heater geometry. Small-scale effects depended on the extent of fluid mixing in the particle vicinity and were typically transient in character, depending on the local particle/fluid structure, temperature and relative movement (Sastry and Palaniappan, 1992a).

A number of models existed on the dilute suspensions (emulsion-type) of sphere within the continuous phase which was not applicable to the concentrated solid-liquid mixture. Only two models for the overall conductivity of mixture had been proposed. Sastry and Palaniappan (1992a) proposed a model for a solid-liquid mixture based on a circuit analysis, in which the mixture was represented as a set of series and parallel resistors. Alternatively, Zhang and Fryer (1993) proposed a unit cell theory whereby the conductivity of a mixture could be estimated by solving Laplace's equation for a 'unit cell' of material.

2.4.1.1 The circuit analogy concept

The circuit analogy concept approximated the behavior of a solid-liquid mixture by considering the arrangement of solid in liquid in terms of three resistances, corresponding to liquid and solid in parallel and liquid in series as shown in Figure 2.8 (Sastry and Palaniappan, 1992a). The sizes of the three resistances depended on the electrical conductivities of the solid and liquid and on the solid fraction. By assuming that all current lines were parallel, the circuit approach may be appropriated in some situations such as high solid fractions. Kanchanakitsakul (1999) found that the relationship between the effective electrical conductivities in multicomponent system of vegetables in salt solution and the electrical conductivities of each components followed this proposed model at volume fractions of 20-60% during heating from 25°C to 125°C.

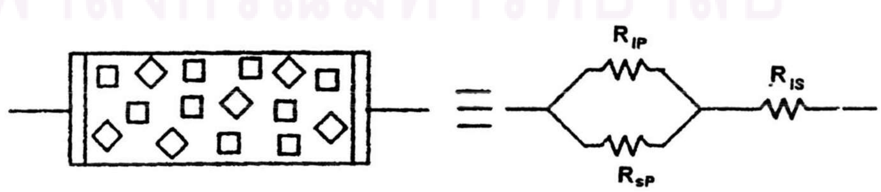


Figure 2.8 Equivalent circuit theory of two component mixture

For two-component mixtures involving large particle populations, the mixture was considered to consist of a continuous (liquid) and a discontinuous (solid) phase. The equivalent electrical circuit was that of parallel liquid (R_{lP}) and solid (R_{sP}) resistances in series with a liquid resistance (R_{lS}) (Sastry and Palaniappan, 1992a). Thus:

$$R = R_{lS} + \frac{R_{lP} R_{sP}}{R_{lP} + R_{sP}} \qquad \text{......................(2.12)}$$

where:

$$R_{lS} = \frac{L_{lS}}{A_{lS}\sigma_l} \qquad \text{......................(2.13)}$$

$$R_{lP} = \frac{L_{lP}}{A_{lP}\sigma_l} \qquad \text{......................(2.14)}$$

$$R_{sP} = \frac{L_{lS}}{A_{sP}\sigma_s} \qquad \text{......................(2.15)}$$

and:

$$A_{lS} = A = A_{sP} + A_{lP} \qquad \text{......................(2.16)}$$

The length of the heater *(L)* is related to the length of each phase:

$$L = L_{lS} + L_{lP} \qquad \text{......................(2.17)}$$

and:

$$L_{sP} = L_{lP} \qquad \text{......................(2.18)}$$

For the present case it was assumed that the area and length of discontinuous phase could be determined from the volume fraction of that phase (vf_s) as follows:

$$A_{sP} = Avf_s^{2/3} \qquad \text{..........................(2.19)}$$

and:

$$L_s = Lvf_s^{1/3} \qquad \text{..........................(2.20)}$$

The voltage distribution was calculated assuming that all equipotential lines were approximately parallel to electrodes. This was a reasonable approximation when the phases were uniformly mixed. After the total resistance was calculated from equation 2.12, the effective electrical conductivity was then calculated from equation 2.4.

For multi-component mixture, it was assumed to contain N types of solid, equivalent to resistances of $R_{sP1}, R_{sP2,}......R_{sPN}$ with volume fraction of $vf_{s1}, vf_{s2},$ ...... $vf_{sN},$ respectively. The total volume fraction could be calculated from equation 2.21 by assuming the length of all particles to be $vf_s^{1/3}$(Kanchanakitsakul,1999).

$$vf_s = \sum_{i=1}^{N} vf_{si} \qquad \text{.................(2.21)}$$

The electrical circuit equivalent to resistance of multi-solids were shown in Figure 2.9.

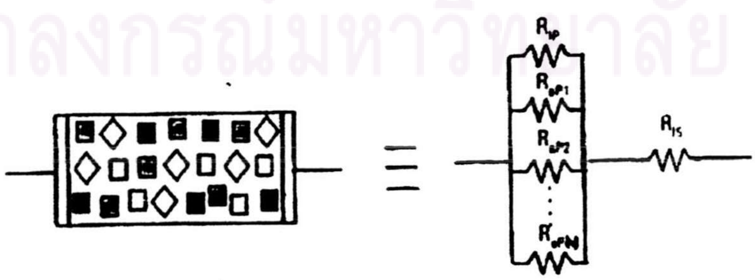


Figure 2.9 Equivalent circuit theory of multi-component mixture

The total resistance was calculated from:

$$R = R_{lS} + R_P \qquad \text{.....................(2.22)}$$

where:

$$R_p = \frac{1}{\dfrac{1}{R_{lP}} + \sum_{i=1}^{N} \dfrac{1}{R_{sPi}}} \qquad \text{.....................(2.23)}$$

$$R_{lS} = \frac{L(1 - vf_s^{\,1/3})}{A\sigma_l} \qquad \text{.....................(2.24)}$$

$$R_{lP} = \frac{Lvf_s^{\,1/3}}{A(1 - vf_s^{\,1/3})\sigma_l} \qquad \text{.....................(2.25)}$$

$$R_{sPi} = \frac{Lvf_s^{\,1/3}}{Avf_s^{\,1/3}\sigma_{si}} \qquad \text{.....................(2.26)}$$

After the total resistance was calculated from equation 2.22, then the effective electrical conductivity could then be calculated from equation 2.4.

2.4.1.2 Unit cell theory

Alternatively, the conductivity of a mixture could be estimated by solving Laplace's equation for a 'unit cell' of material (Zhang and Fryer, 1993). It was assumed that the distribution of particles in the liquid was uniform so that the ohmic heating cell could be divided into a number of 'unit cells' each containing a number of particles (Figure 2.10). Each unit cell was identical, so that it was only necessary to model one unit cell to predict the behavior of the whole. de Alwis and Fryer, (1992) and Zhang and Fryer (1993) developed this approach by consider a possible cell pattern in which particles were distributed on a cubic lattice and cell size could be adjusted to solve for any solid fraction.

Voltage distribution within a unit cell was calculated by solving Laplace's equation (equation 2.11) with appropriate boundary conditions, i.e., no current flow across the boundary and uniform voltage on the electrodes. The Laplace's equation was governed with an electrical conductivity in which it was a function of position and temperature. Finite element program was used to simulate the model. For a 2-D situation, equation 2.11 could be written as:

$$\frac{\partial}{\partial x}\left(\sigma_x \frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial y}\left(\sigma_y \frac{\partial V}{\partial y}\right)=0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots(2.27)$$

Although more computation work was required, the unit cell approach was a more general approach to a low concentration solid fraction including an isolated particle. In practice, the particles were unlikely to be uniformly distributed on the lattice as assumed in the unit cell model, which would affect the accuracy of the model. It was possible that grouping of particles would lead to current channeling in a way that it could not be predicted by this approach (Zhang and Fryer, 1993).

Comparing the two models for the calculation of particle heating rates, the calculation based on unit cell model was more complex in time and computing power than the use of circuit analogy (Zhang and Fryer, 1995). However, it has been shown that the circuit analogy could give significant errors at low solid fractions, especially the case with isolated particle.

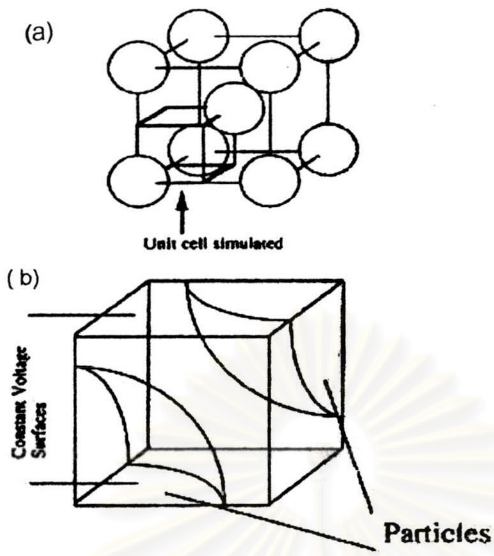


Figure 2.10 'Unit cell model' for overall electrical conductivity
(a) unit cell body centered-cubic particles, showing modeled section
(b) enlarged unit cell

2.4.2 Temperature distribution

It was necessary that all parts of the food, both solid and liquid, was commercially steriled after ohmic processing. It was thus necessary to be able to predict heating rates throughout the two phases. Conventional processes were controlled by thermal properties such as thermal conductivity and specific heat. Ohmic heating would, however, critically depend on the electrical conductivity of the food material and the electrical conductivity distribution of the mixture as it determined the rate of heat generation as in equation 2.3 (Sastry and Li, 1996).

The temperature distribution at any instant of the heating process could be calculated by solving the energy balance equation with a heat generation term and applying the appropriate initial and boundary conditions. Both the thermal (equations 2.6-2.7) and electrical problems (equations 2.3, 2.5 and 2.10) had to be solved simultaneously. The energy generation rate during ohmic heating (equation 2.3) was directly related to the current induced by voltage gradient (field strength, ∇V) and a temperature-dependent electrical conductivity (equation 2.5).

In practice, assumptions were necessary to simplify the problem. In static heater, by assuming that the system was thermally and electrically insulated and the conduction and convection heat transfer occurred infinitely fast, i.e. the liquid temperature was uniform. The system resistance could be estimated by assuming a uniform electrical conductivity throughout the system so the heat generation of the system could be calculated by including the temperature-effective conductivity relationship in equation 2.3 (Fryer *et al.*, 1993). The temperature dependence of effective electrical conductivity could be rewritten from equation 2.5 as:

$$\sigma = a + bT \qquad \text{......................(2.28)}$$

then, it was substituted into equation 2.3 to be:

$$Q = |\nabla V|^2 (a + bT) \qquad \text{......................(2.29)}$$

From equation 2.7:

$$G = \frac{dT}{dt} = \frac{Q}{\rho C_p} = \frac{\sigma |\nabla V|^2}{\rho C_p}$$

The relationship in equation 2.29 was then substituted into equation 2.7 and integrated to give equation 2.30 as followed (Fryer *et al.*, 1993):

$$T = \frac{1}{b}\left\{(a + bT_0)\exp\left[\frac{bE^2 t}{\rho C_p}\right] - a\right\} \qquad \text{..................(2.30)}$$

2.4.3 Experimental studies of temperature prediction

deAlwis and Fryer (1990) developed a 2-D model using finite-element approach to calculate the temperature of solid and liquid based on unit cell theory. The program was used firstly to calculate the voltage distribution by solving Laplace's equation in which the electrical conductivity was a function of both position and temperature. For a 2-D situation, the Laplace's equation could be rewritten as equation

2.27. Once the voltage distribution was calculated, then the heat generation could be calculated by the network theory approach, by considering each triangular element as an isolated network with nodal voltage known by solution of equation 2.27. Current values were readily found by solving equations analogous to equation 2.27, and thus heat generation was the summation of voltage and current. Temperature distributions were subsequently determined by differential equations governing two transient heat generation and conduction. The predicted temperature was compared with those obtained from experiment heating of single piece of lamb meat 20x20x15 mm in saline solution of equivalent electrical conductivity of 0.45 S/m (Figure 2.11 a, b); a piece of potato 40x10x20 mm with conductivity of 0.038 S/m in salt solution of 0.58 S/m (Figure 2.12). Simulations showed good agreement between experimental and predicted result. The approach was suggested to be suitable but of expensive in computer time.

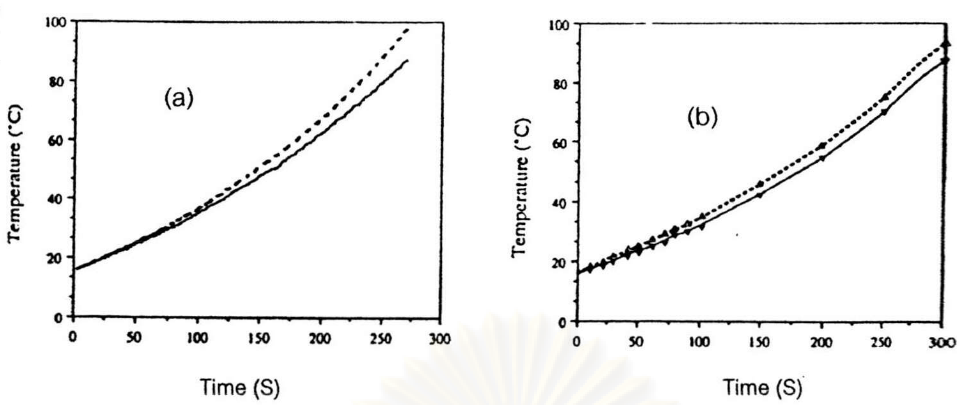


Figure 2.11 Heating of lamb meat in brine: (a) experiment, (b) simulation.
(- - - -) solid, (____) liquid.
Source: deAlwis and Fryer (1990)

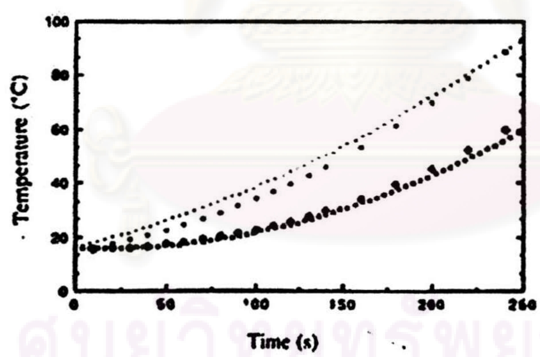


Figure 2.12 Comparison of the experimental and modeled temperature of a potato piece in brine Solid: (•) experiment, (••••) simulation,
Liquid: (.) experiment, (.....) simulation.
Source: deAlwis and Fryer (1990)

Sastry and Palaniappan (1992a) studied the mixture of potato cubes in sodium phosphate solutions of various concentrations using the three dimensional finite element method for temperature prediction of solid and liquid. Particle population ranged from two 1.5 cm potato cubes precisely located (at 1.9 cm from the center on either side within the 10 cm ohmic chamber) to randomly scattered particles (20 and 30 cubes of 0.8cm). The heat transfer problem of particle was the conduction heat transfer equation with temperature-dependent internal energy generation with a time-dependent boundary condition while the liquid temperature at each successive time increment could be calculated from the energy balance equation by assuming a rapid mixing and no temperature gradient within the liquid. For the case of two particles precisely positioned, the equivalent resistance was calculated by separately considering zones containing particles from those without particles, while for the case of large populations, the equivalent electrical circuit-theory based approach was used. The comparisons between model and experiment results were also shown in Figure 2.7 above. It was concluded that the predicted temperatures were in satisfactory agreement with experimental findings, due to considering factors such as potential for experimental error and model assumptions.

Bulk convection in the liquid phase became important when temperature variation existed in static system. Fryer *et al.* (1993) studied the convection effect on temperature in static heater by placing electrical insulators made of wood and aradite adhesive of different geometries: a cylinder of 38 mm diameter and a rectangular block of 44x23 mm in CMC solution with equivalent conductivity but different viscosity. Temperature at two positions, at the side (point 1) and the front (point 2) were monitored upon heating. It was found that the presence of insulators distorted the electric field distribution significantly and consequently caused the local temperature variations in liquid around the particles. For the low-viscosity system, the solid temperature was close to that of the liquid, due to convective mixing and rapid heat transfer. The temperature prediction was followed equation 2.30 which was simplified by assuming that conduction and convection heat transfer occurred infinitely fast, slightly overprediction of the solution was found in both geometry of solid samples (Figure 2.13).

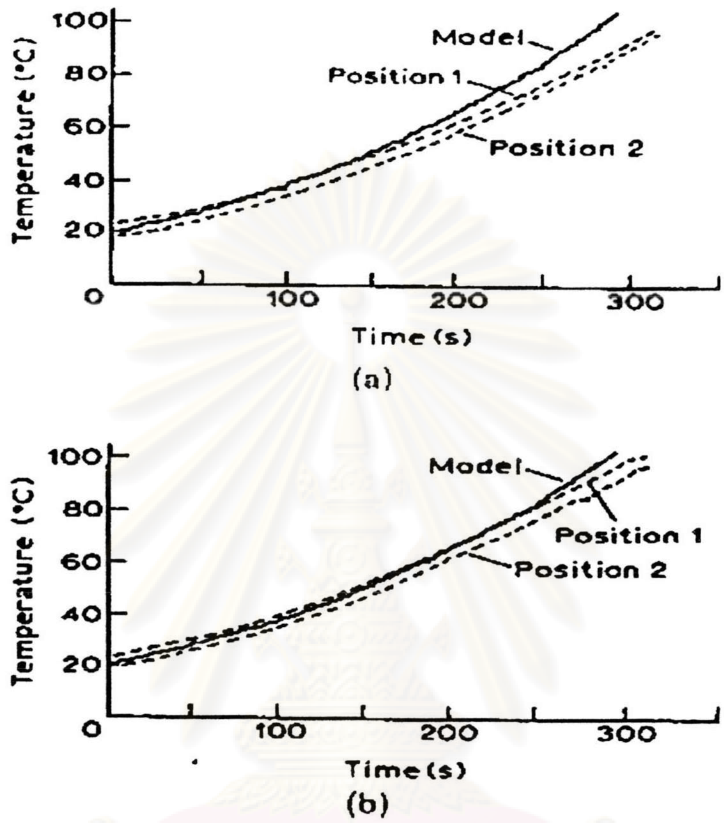
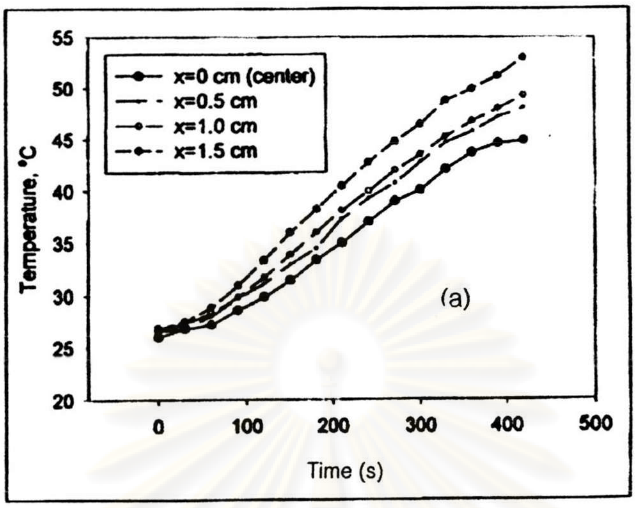


Figure 2.13 Ohmic heating of an insulating materials in salt solution
(a) a wooden cylinder (b) a rectangular insulating block
Source: Fryer *et al.* (1993)

Fu and Hsieh (1999) followed the study of deAlwis and Fryer (1990) by investigating the temperature prediction of the mixture of potato-sodium sulfate solution having different sample dimensions, using finite element method calculated by commercial software. A thin rectangular slice of potato (1.4x 6.2x 0.35cm) represented a two-dimensional with the minimum third dimension to minimize natural convection during ohmic heating. Temperatures at four locations, at the center and separated 5mm apart along the long axis, were measured. It was found that the center point was the coldest point throughout the heating. The predicted temperature from the model was higher than that from the experiment. The difference was suggested to be due to the heat loss to the environment and inaccurate physical property values used in the model (Figure 2.14).

Plaichoom (2002) studied the pasteurization of drinking yoghurt with 1 cm pineapple cube at 0, 5, 10, 15 and 20% during 20-80°C and using the equation 2.30 for temperature prediction. It was found that the predicted temperature was far more overpredicted than the experimental temperature. It was suggested to be due to the effect of size, shape and solid orientation. However, it could predict well if the homogeneous samples were prepared by homogenizing the solid into the liquid.



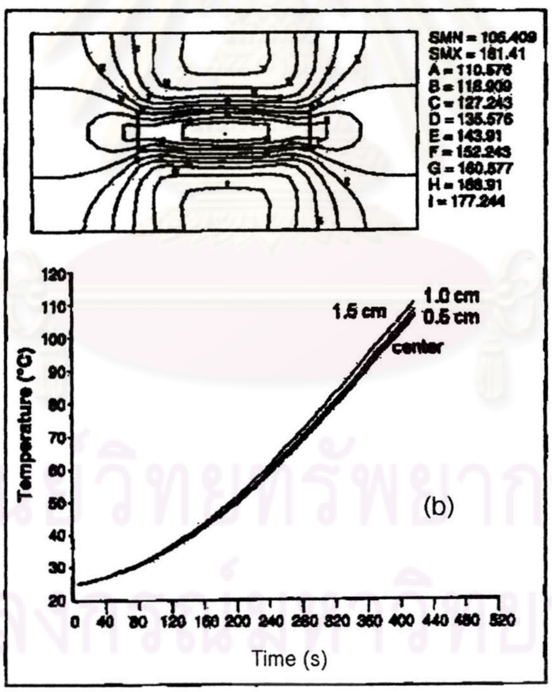


Figure 2.14 Temperature of a potato piece (1.4x 6.2x 0.35cm) in sodium phosphate solution (a) experiment (b) model

Source: Fu and Hsieh (1999)