CHAPTER IV

RESULTS AND DISCUSSION

4.1 Design of the ohmic heating cell

A static ohmic heater designed in this study (Figure 3.1-3.4) was investigated for the working performance. Application of alternate current at 50 Hz, 10-20 V/cm to the 0.1M NaCl showed slight purple color formed on the electrode surfaces due to the unavoidable electrolysis reaction (Kanchanakitsakul, 1999) but neither corrosion on the electrode surfaces nor metal contamination in the salt solution was observed. Polishing of electrode surfaces with ultrafine sand paper (#1000) could provide the uniform clear surfaces. The device was tested for accuracy and found that the differences between the determined electrical conductivity values and the reported values (Palaniappan and Sastry, 1991a,b) of three reference salts were 0.85–6.75 % (Table 4.1), indicating satisfactory accuracy for this device.

Table 4.1 Comparison of conductivities at 25°C between reference and measured value

Reference material	Reference electrical conductivity value (S/m)	Measured electrical conductivity (S/m)	% difference
0.1 M NaCl	1.03	1.002±0.002	2.64
0.02 M NaCl	0.2	0.213±0.001	6.75
0.1M NaH_2PO_4	0.63	0.635±0.004	0.87

4.2 Effect of voltage and frequency on electrical conductivity of solid foods

4.2.1 Effect of voltage

The σ-T curves of blanched and soaked potato and white radish, cooked surimi, and cooked pork with different voltage levels were shown in Figure 4.1 and corresponding data in Table 4.2.The linear relationship ($R^2 = 0.99-1$) between σ and temperature was found. It indicated the increase in conductivity with temperature due to the increasing in ionic mobility (Plaichoom, 2002; Marcotte, Trigui, and Ramaswamy, 2000; Kanchanakitsakul, 1999; Yongsawatdigul *et al.*, 1995; Wang and Sastry,1993; deAlwis and Fryer, 1992; Palaniappan and Sastry, 1991a,b; Halden *et al.*,1990). Applying different levels of voltage gradients gave no significant difference on σ ($p > 0.05$) for all examined pretreated samples (Figure 4.1). Statistical analysis of electrical conductivities at 25°C (σ_{25}) and temperature coefficients ($m\sigma_{25}$) of the three voltage levels was presented in Appendix A (Table A1-4). This indicated that voltage gradient had no significant effect on σ of both pretreated vegetables and animal samples. In order to give clear explanation, the experiments on raw samples were conducted to compare this effect. The σ-T curves of raw samples as affected by voltage were shown in Figure 4.2. It was clearly shown that the voltage gradient influenced the σ of raw vegetable samples but not animal samples.

For raw potato and white radish, the σ-T curves were non linear and increased as the voltage gradient increased (Figure 4.2 a-b) Changes in slopes occurred at around 60°C indicating the critical structure changes during ohmic heating which agreed with those reported in carrot and beetroot (Palaniappan and Sastry, 1991a; Halden *et al.*, 1990). Applying high voltage would accelerate the electro-osmotic and electroporation phenomenon during ohmic heating of raw vegetables. Electro-osmosis occurred due to the enhancement of molecular diffusion through capillary action (Halden *et al.*, 1990; Palaniappan and Sastry, 1991a; Fryer *et al.* 1993; Wang and Sastry, 1993, 1997b; Lima *et al.* 1999) while electroporation was the formation of pores on the cell membrane resulted in increases in mass transfer as influenced by electric field (Halden *et al.*, 1990; Schreier, Reid, and Fryer, 1993; Lima and Sastry, 1999; Wang and Sastry, 2002; Lima *et al.*, 2001; Zhong and Lima, 2003).

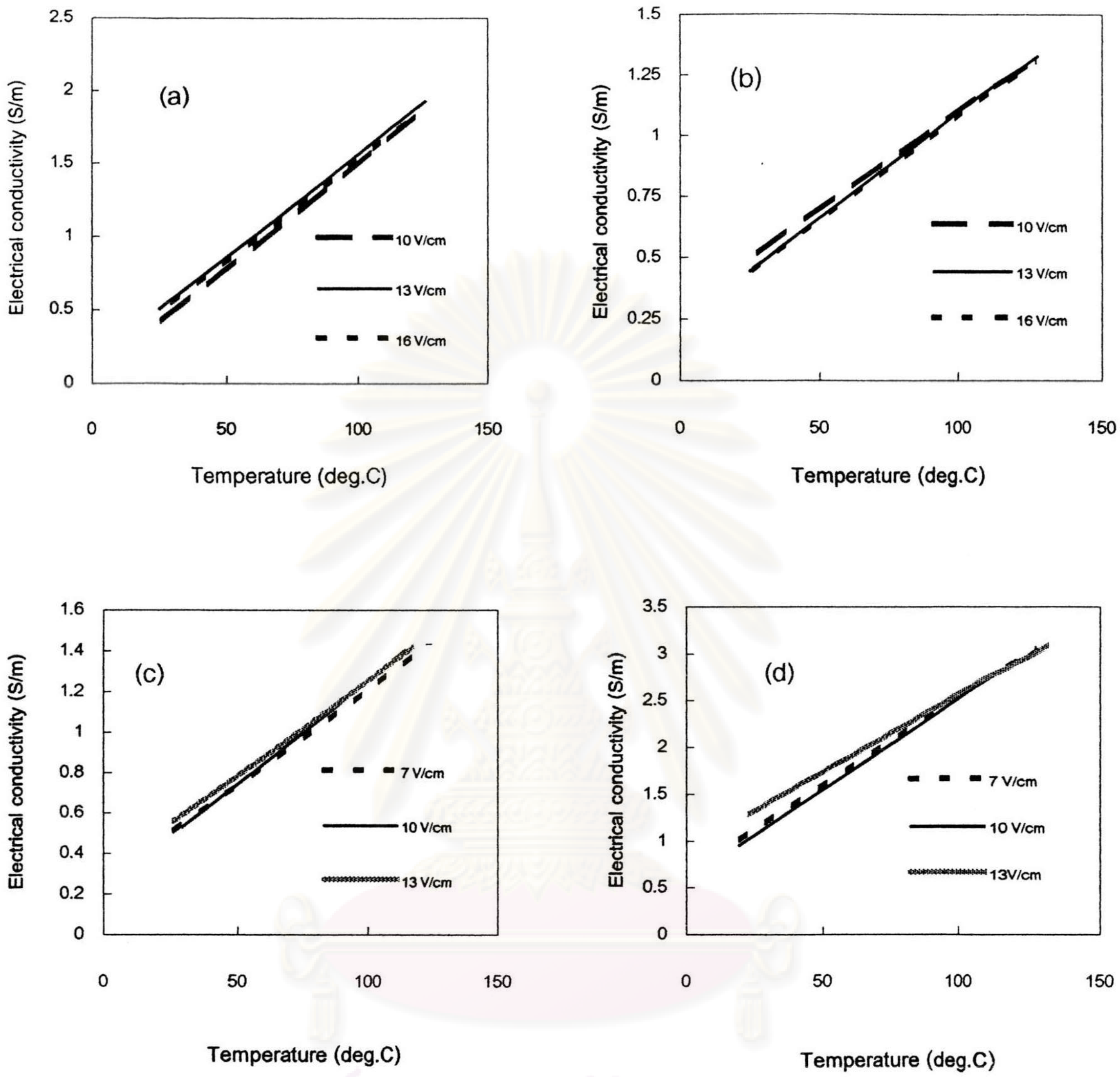

Figure 4.1 Effect of voltage gradient on electrical conductivity of solid food (a) blanched and soaked potato, (b) blanched and soaked white radish, (c) cooked pork, (d) cooked surimi

Table 4.2 Means of regression parameters of electrical conductivity as a function of temperature of solid samples at various voltage gradients

Sample	Voltage gradient (V/cm)	σ_{25} (S/m)	$m\sigma_{25}$ (S/m°C)
Blanched and Soaked potato	10	0.5670 ± 0.02	0.0148 ± 0.001
	13	0.5050 ± 0.05	0.0141 ± 0.001
	16	0.4754 ± 0.01	0.0141 ± 0.001
Blanched and Soaked white radish	10	0.4893 ± 0.02	0.0083 ± 0*
	13	0.4406 ± 0.03	0.0087 ± 0.001
	16	0.4329 ± 0.04	0.0087 ± 0.005
Cooked pork	7	0.4944 ± 0.04	0.0096 ± 0.004
	10	0.4870 ± 0.05	0.0102 ± 0.006
	13	0.5415 ± 0.04	0.0096 ± 0.004
Cooked surimi	7	1.1065 ± 0.10	0.0193 ± 0.002
	10	1.0634 ± 0.20	0.0195 ± 0.002
	13	1.3112 ± 0.01	0.0170 ± 0.001

$\sigma = \sigma_{25} + m\sigma_{25}(T-25)$ (equation3.2)

* 0 indicates value less than 0.001

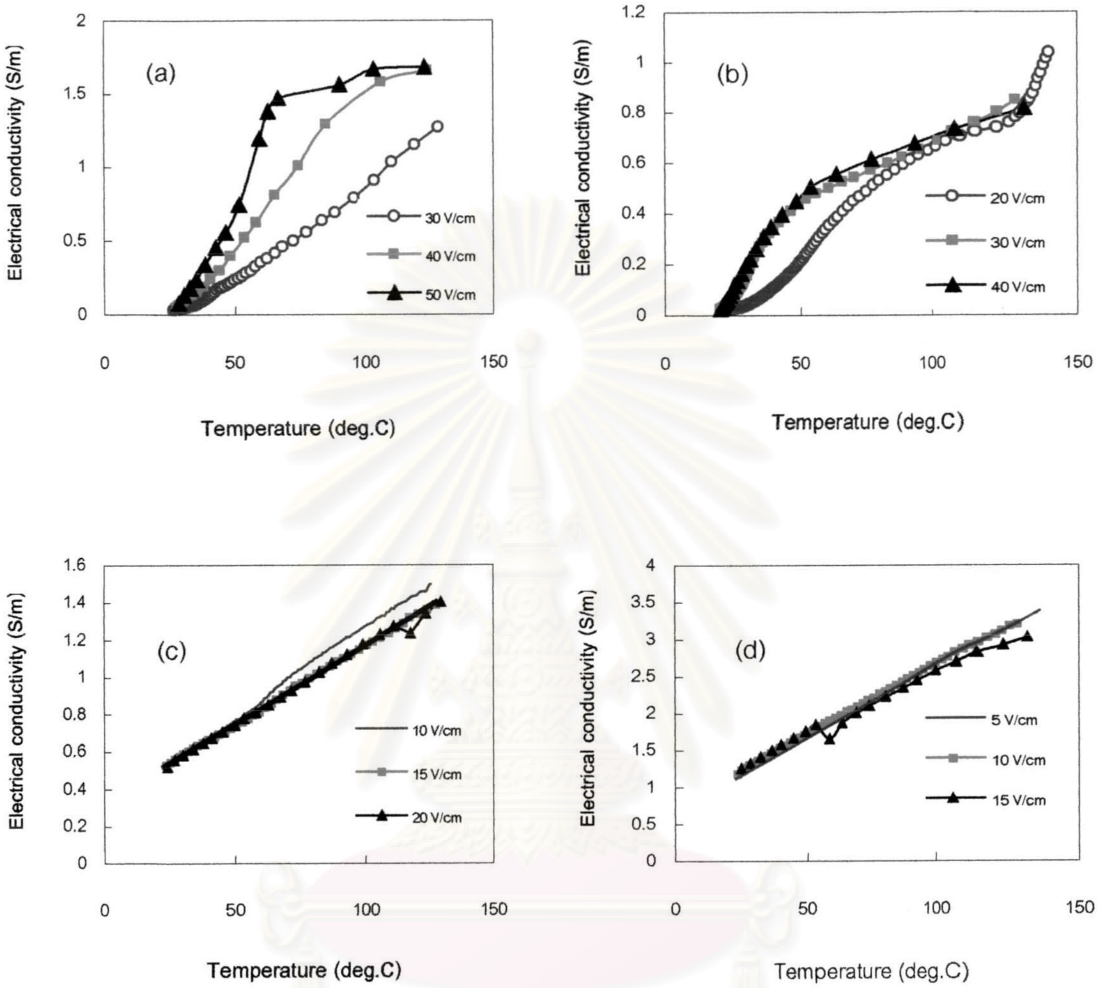

Figure 4.2 Effect of voltage gradient on electrical conductivity of raw solid foods
(a) raw potato, (b) raw white radish,
(c) raw pork, (d) raw surimi

For blanched and soaked vegetable samples, the σ -T curves were shown in Figure 4.1 a,b. Unlike the raw vegetables, the σ-T curves of blanched samples were linear and no significant effect of voltage gradient was found as the blanched and soaked samples may be completely stabilized and equilibrated. During blanching, structural changes such as cell wall breakdown, expulsion of gas bubble, starch gelatinization, tissue softening and protein denaturation that may alter the ionic content had already occurred. Preheating by blanching caused the irreversible change in cellular structure. Thus, the electro-osmosis and electroporation would not occur during apply voltage to blanched and soaked potato and white radish. The result was similar to Wang and Sastry (1997b) who compared the raw potato, carrot and yam to those preheated to 80°C and found that preheated samples had linear curves with higher conductivities compared to the fresh one with non-linear and relative lower conductivities.

For surimi and pork, the voltage gradient did not significantly ($p > 0.05$) affect the σ either raw (Figure 4.2.c,d) and cooked (Figure 4.1 c,d). The drop and in σ–T curves were detected in raw pork at 20 V/cm (Figure 4.2c) and raw surimi at 15 V/cm (Figure 4.2d) which might be due to the oxidation of electrodes. Applying voltage to animal samples would not likely to enhance the fluid motion as those occurred in plant cells due to differences in cellular structure. Fibrous structure with lots of non-conductive trapped air in plant compared to protein network embedded with small non-conductive fat globules in animal as well as rigid cell wall versus cell membrane microstructures were most likely to cause large differences in food conductivity. The result agreed with Yongsawatdigul *et al.* (1995) who found no significant voltage effect on surimi paste.

4.2.2 Effect of frequency

The σ-T curves of blanched and soaked potato and white radish, cooked surimi and cooked pork at three frequencies of 50, 500 and 1000 Hz. were shown in Figure 4.3 and corresponding data in Table 4.3. The σ linearly increased with temperature at each frequency. The frequency did not significantly ($p > 0.05$ and Tables A5-8 in Appendix A) affect the σ of all samples. The result was different from those reported in raw vegetables (Lima *et al.*, 1999; Lima and Sastry, 1999; Imai *et al.*, 1995) that low frequency might enhance the cell fluid motion and damaged cell wall of plant cell. As the samples in this experiment had been thermal pretreated, the cell fluid might leak out of the cell due to changes in cellular structure. (Halden *et al.*, 1990). Thus, frequency would not possibly induce the electro-osmosis and electroporation in the pretreated samples as those reported in raw vegetables. This result may indicate that frequency did not influence the ionic mobility.

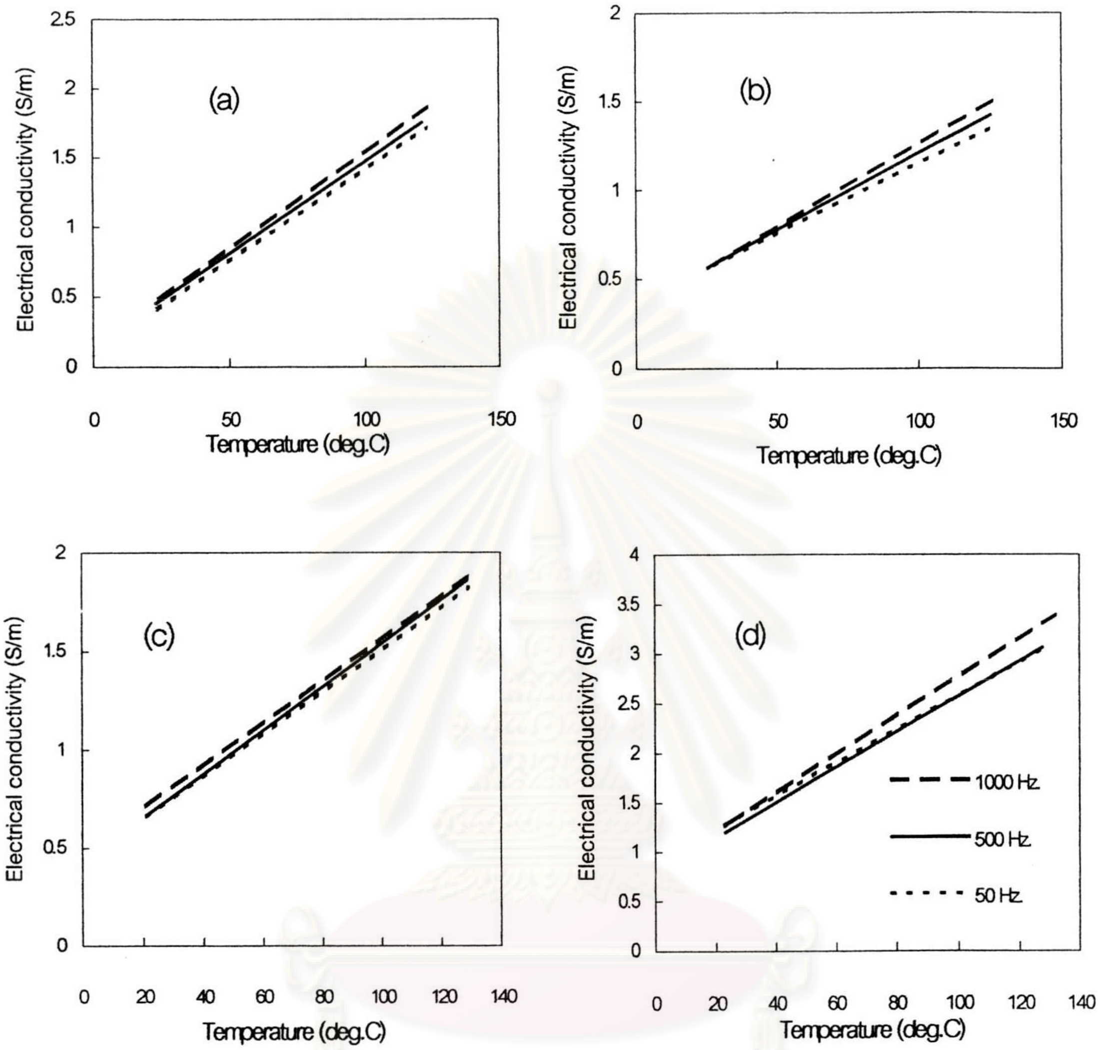

Figure 4.3 Effect of frequency on electrical conductivity of solid foods (a) blanched and soaked potato, (b) blanched and soaked white radish, (c) cooked pork, (d) cooked surimi

Table 4.3 Means of regression parameters of electrical conductivity as a function of temperature of solid samples at various frequency

Sample	Frequency (Hz.)	σ_{25} (S/m)	$m\sigma_{25}$ (S/m°C)
Blanched and	50	0.8789 ± 0.03	0.031 ± 0.001
Soaked potato	500	0.9282 ± 0.06	0.031 ± 0.001
	1000	0.9459 ± 0.04	0.032 ± 0.001
Blanched and	50	0.5553 ± 0.02	0.0079 ± 0*
Soaked white	500	0.5620 ± 0.03	0.0086 ± 0*
radish	1000	0.5555 ± 0.04	0.0094 ± 0.001
Cooked pork	50	0.7013 ± 0.05	0.0108 ± 0.004
	500	0.7107 ± 0.04	0.0110 ± 0.005
	1000	0.7571 ± 0.06	0.0108 ± 0.004
Cooked surimi	50	1.3110 ± 0.10	0.0170 ± 0.002
	500	1.2335 ± 0.10	0.0179 ± 0.003
	1000	1.3022 ± 0.10	0.0196 ± 0.001

$\sigma = \sigma_{25} + m\sigma_{25}(T-25)$ (equation3.2)

* 0 indicates values less than 0.001

4.3 Factors affecting electrical conductivity of model liquid foods

4.3.1 Effect of voltage

The σ of 1% salt solution subjected to 100, 200 and 260V (equivalent to 18.2, 36.4 and 47.3 V/cm) at 50 Hz was shown in Table 4.4, corresponding to Figure 4.4. No significant difference on electrical conductivity of salt solution ($p>0.05$) was influenced by voltage (TableB1 in Appendix B). The voltage subjected to pure sodium chloride solution in this study would accelerate the ionic mobility. Since ionic mobility depended on only temperature, not the heating rate (Palaniappan and Sastry, 1991b). Different voltages applied which provided different heating rate (equation 2.3) would not cause differences in σ. The result agreed with the experimental study of Palaniappan and Sastry (1991b) who reported that the σ was not directly influenced by the voltage, only the transition points at which small hydrogen gas bubbles presented at the end of heating was decreased as the voltage increased. However, the result was different from those found in 5% pineapple in drinking yoghurt because it was a mixture between solid and liquid so that electro-osmotic and electroporation may expected (Plaichoom, 2002).

4.3.2 Effect of frequency

The σ of salt solution as affected by frequency at 50,500, and 1000 Hz. were shown in Table 4.5, corresponding to Figure 4.5. Similar to the effect of voltage, frequency did not significantly ($p>0.05$) affect the σ of salt solution (Table B2 in Appendix B). This may indicate that frequency did not influence the ionic mobility of the electrolyte. Reducing the electrolytic reaction by increasing frequency as reported by Wu *et al.* (1995) was also found. As oxidation of electrode surfaces decreased when applying high frequency so high frequency could overcome the electrode corrosion due to electrolytic reaction.

Table 4.4 Means of estimated parameters of electrical conductivity as a function of temperature of 1% salt solution at various voltage

Voltage (V)	σ_{25} (S/m)	$m\sigma_{25}$ (S/m°C)
100	1.7262 ± 0.0204	0.0311 ± 0.0001
200	1.7743 ± 0.0122	0.0321 ± 0.0009
260	1.7825 ± 0.0090	0.0324 ± 0.0006

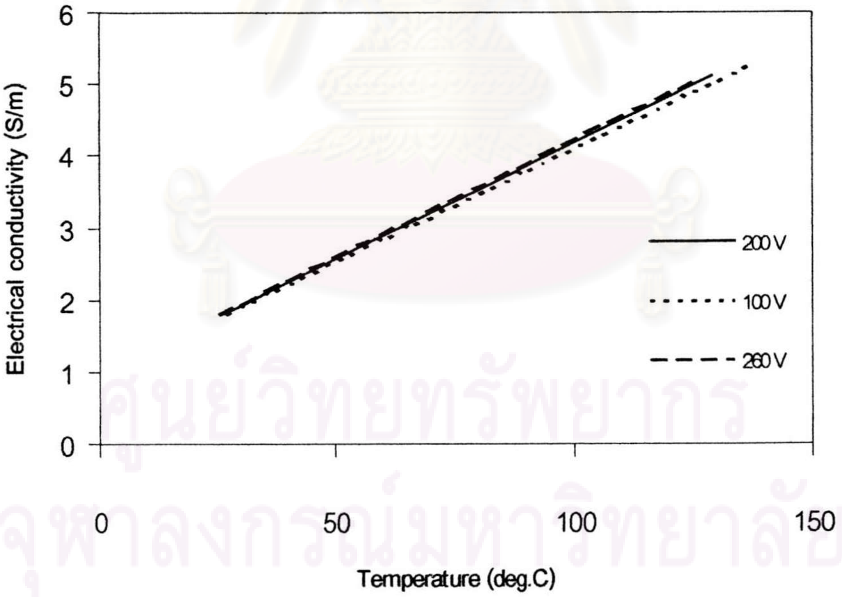

Figure 4.4 Effect of voltage on electrical conductivity of 1% salt solution

Table 4.5 Means of estimated parameters of electrical conductivity as a function of temperature of 1% salt solution at various frequency

Frequency (Hz.)	σ_{25} (S/m)	$m\sigma_{25}$ (S/m°C)
50	1.7350 ± 0.0065	0.0311 ± 0.0001
500	1.7354 ± 0.0057	0.0305 ± 0.0004
1000	1.7254 ± 0.0040	0.0308 ± 0.0003

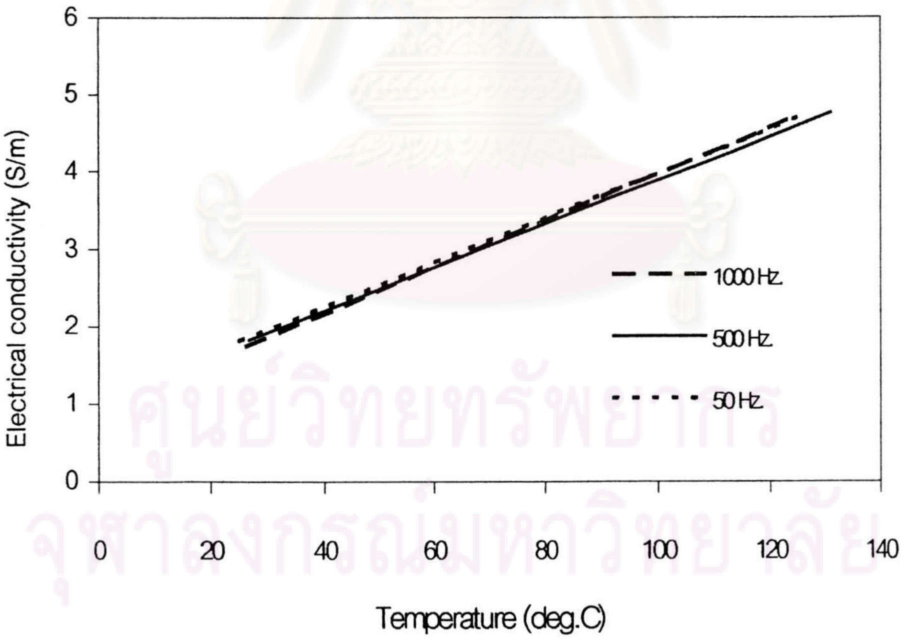

Figure 4.5 Effect of frequency on electrical conductivity of 1% salt solution

4.3.3 Effect of salt

It was clearly shown in Table 4.6 and Figure 4.6 that the σ highly depended on salt concentration ($p \leq 0.05$). Statistical analysis was shown in TableB3 in Appendix B. Increasing salt concentration from 0.5 to 1 and 1.5% significantly raised the σ at 25°C from 0.943 to 1.783 and 2.752 S/m. The σ values at 125°C increased from 2.653 at 0.5% salt to 4.964 and 7.172 S/m at 1 and 1.5% salt. Higher salt contents also caused high temperature dependence by considering the temperature coefficient ($m\sigma_{25}$, Table 4.6) which were increased from 0.0171 to 0.0318 and 0.0442 S/m, respectively.

Adding more salt in solution resulted in an increase in ions (Na^+ and Cl^-) for conducting electrical current which therefore increased conductivity. The result agreed with those reported by Palaniappan and Sastry (1991a), Wang and Sastry (1993), Yongsawatdigul *et al.* (1995), and Marcotte *et al.* (2000).

Table 4.6 Means of estimated parameters of electrical conductivity as a function of temperature of salt solution at different concentration of salt at 50Hz. and 9.1 V/cm

Concentration (%w/w)	σ_{25} (S/m)	$m\sigma_{25}$ (S/m°C)
0.5	0.9432 ± 0.02	0.0171 ± 0.002
1	1.7838 ± 0.02	0.0318 ± 0.003
1.5	2.7527 ± 0.01	0.0442 ± 0.005

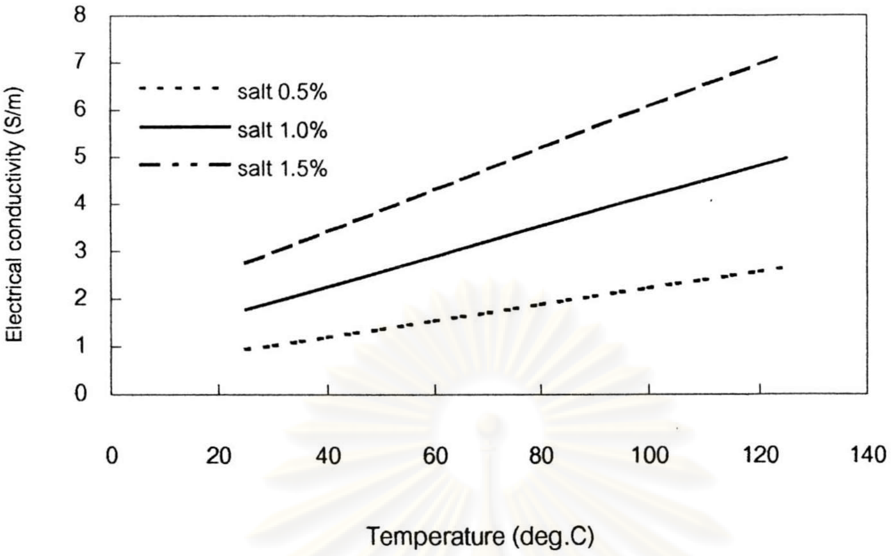

Figure 4.6 Effect of salt on the electrical conductivity of salt solution

4.3.4 Effect of starch

Table 4.7 represented the σ of 1% salt solution with added starch 0-8% and corresponding σ–T curves were shown in Figure 4.7. Preliminary examination agreed with those reported by Marcotte *et al.* (1998) that starch itself conducted heat poorly. This indicated that the ionic content originally presented in starch paste was relatively low. Addition of 1% salt in starch paste studied was to assist the ability of the paste to conduct heat. From Figure 4.7, the σ decreased significantly ($p \leq 0.05$) as the starch concentration increased from 2 to 8% (Table B4 in Appendix B). It could be explained that starch decreased the unbound water in the cell matrix structure as the free water was bound and entrapped during gelatinization. (Wang and Sastry, 1997a). The role of water to ionic mobility was presented by Yongsawatdigul *et al.* (1995) that electrical conductivity of surimi paste containing the same salt content was higher at higher moisture content. They explained that more ion solvation could increase ionic mobility. In addition, more starch addition resulted in higher viscosity (Marcotte *et al.*, 1998) and might retard the ionic mobility. Cation-starch interaction in the presence of salts caused an increase in volume of starch granule and viscosity (Bircan and Barringer, 1998; Sudhakar, Singhal, and Kukarni, 1995b).

On the other hand, evidences had shown that high concentration of starch may be related to high ion released. Potato starch itself contained 0.06-0.09% of phosphorus in starch granules, present as phosphoric acid in amylopectin called amylophosphoric acid (Lisinska and Leszezynski, 1989). Investigation of Chaiwanichsiri *et al.* (2001) showed that σ of variety of starches including potato starch increased during gelatinization due to the release of ions from starch granules. Study of Marcotte *et al.* (1998) demonstrated that the conductivity of 'Thermoflo' starch paste at 2, 4, and 6% slightly increased from 0.051 to 0.059 and 0.068 S/m at 25°C, respectively. The above reviews indicated that high σ would be obtained in the gelatinized starch with higher starch concentration which was contradicted to that investigated in this study. This could be explained that in their systems without salt added, the ions released from starch granules would directly associated with the σ increased. Whereas in this experiment in which 1% salt was added, the ions from salt appeared to dictate the trend of σ rather than the relative small amount of ions released from the starch. Upon the result investigated, the factors which affected the ionic mobility had more impact to the system studied than the slight increase in ionic contents.

4.3.5 Effect of sugar

Model system of 1% salt with added sugar at 2, 5, 10, and 15% were investigated. The σ data was shown in Table 4.8 and corresponding σ-T curves in Figure 4.8. It was found that the σ of salt solution, both the σ_{25} and $m\sigma_{25}$ significantly decreased ($p \leq 0.05$) upon heating as the sugar increased from 2 to 15% (Table B5, Appendix B). Within the range of sugar examined, the σ_{25} reduced from 1.7604 without sugar to 1.1874 S/m with 15% sugar while the $m\sigma_{25}$ decreased from 0.0309 to 0.0247, corresponding to 30 and 20% reduction. These might be caused by the decrease in ionic mobility as well as those found in starch effect. In addition, sucrose itself is a non-electrolyte so it could not conduct ohmic heat (Zumdahl, 1997).

Table 4.7 Means of estimated parameters of electrical conductivity as a function of temperature of 1% salt solution with starch at various concentration at 50Hz. and 9.1 V/cm

Starch concentration (%w/w)	σ_{25} (S/m)	$m\sigma_{25}$ (S/m°C)
0	1.7838 ± 0.01	0.0318 ± 0.001
2	1.7209 ± 0.01	$0.0286 \pm 0^{*}$
4	1.7325 ± 0.01	0.0266 ± 0.001
6	1.5645 ± 0.01	0.0259 ± 0.001
8	1.4703 ± 0.01	0.0252 ± 0.001

[*] 0 indicates value less than 0.001

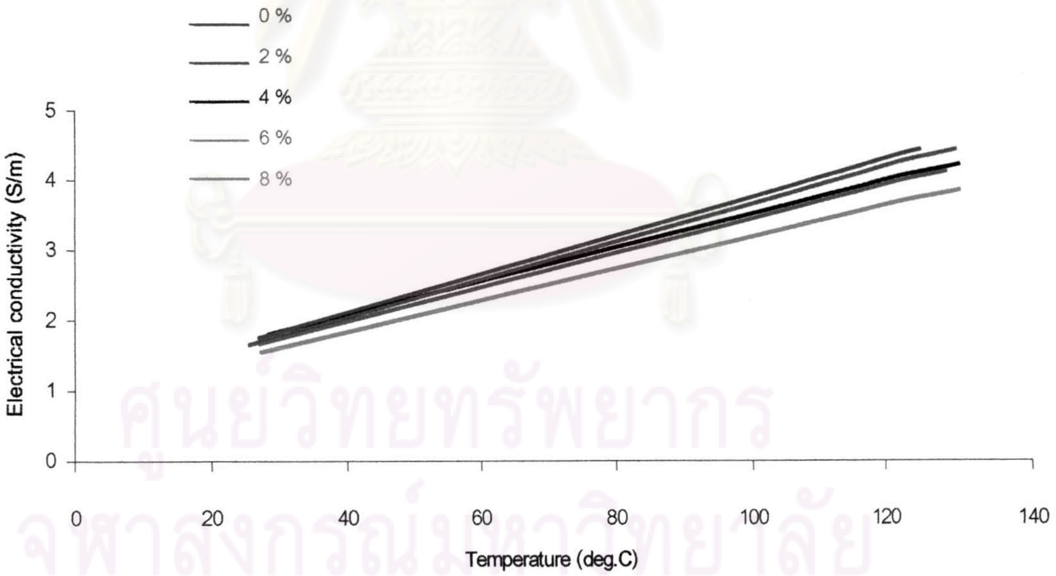

Figure 4.7 Effect of starch concentration on electrical conductivity of 1% salt solution

Table 4.8 Means of estimated parameters of electrical conductivity as a function of temperature of 1% salt solution with sugar at various concentrations at 50 Hz. and 9.1 V/cm

Sugar concentration (%w/w)	σ_{25} (S/m)	$m\sigma_{25}$ (S/m°C)
0	1.7604 ± 0.01	0.0309 ± 0*
2	1.6185 ± 0.02	0.0302 ± 0*
5	1.5237 ± 0.03	0.0289 ± 0.001
10	1.3352 ± 0.01	0.0262 ± 0.001
15	1.1874 ± 0**	0.0247 ± 0.001

* 0 indicates values less than 0.001

** 0 indicates value less than 0.01

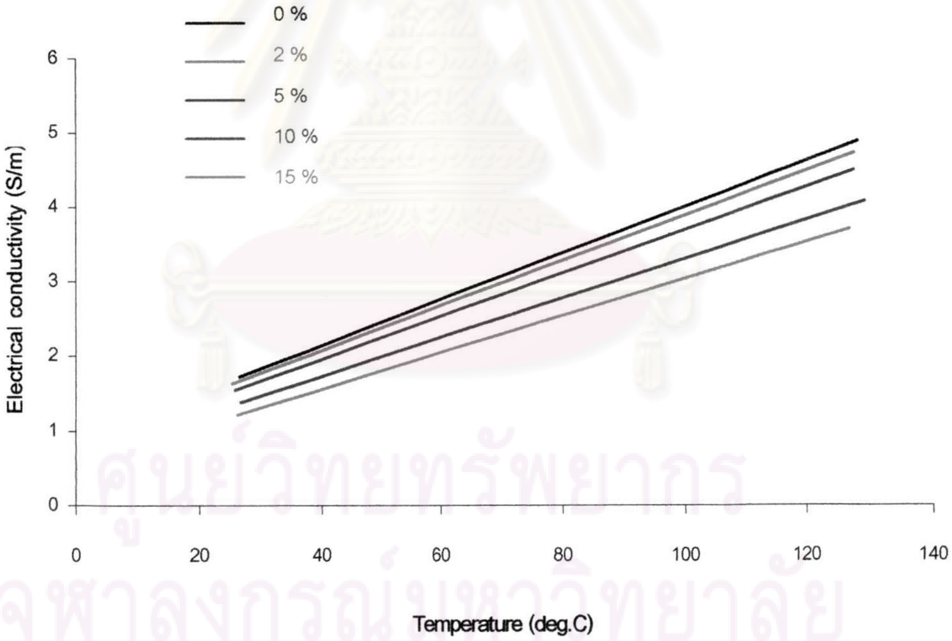

Figure 4.8 Effect of sugar concentration on electrical conductivity of 1% salt solution

4.4 Correlation between ingredients and electrical conductivity of model liquid

As the starch paste in this experiment was preheated to 80°C prior to ohmic heating. It was at least 14°C higher than the normal gelatinization temperature range for pure starch slurry which was reported to be 56-66°C (Lisinska and Leszezynski, 1989). In the presence of sugar or salt in starch, the increase in the gelatinization temperature was reported (Chinachoti *et al.*, 1991a,b; Beleia *et al.*, 1996; Sudhakar, Singhal, and Kukarni, 1995a). Addition of 10 and 20% sucrose in 5% potato starch was found to raise the endset temperature of pure starch from 69.8 to 71.6 and 74.3°C which was 1.8 and 4.5 degree higher (Chaiwanichsiri, Miyawaki, and Suzuki, 2004). Addition of sodium chloride up to 1% was found to raise the gelatinization temperature of pure corn starch from 86.6 to 89°C which was 2.4 degree higher (Sudhakar *et al.*, 1995a) while the gel peak temperature of wheat starch with starch to free water ratio of 40:60 increased from 66.15 to 72.88°C which was 4.3 degree higher (Chinachoti *et al.*, 1991a,b). Water was another important parameter for gelling starch, as it was reported that potato starch suspension of above 20% was found to decrease gelatinization due to an insufficient amount of water (Lisinska and Leszezynski, 1989). The maximum starch concentration used in this study was 8% which was enough to accomplish gelatinization. Fully gelatinization was confirmed by determining the gelatinization temperature using Differential Scanning Calorimetry and it was found that the endset temperature of 1%salt-12%sugar-8%starch combination which was the highest ingredient ranges used in this study was 77.82°C. Thus, fully gelatinization was ensured.

The relationships between electrical conductivity and temperature at various combinations of starch, salt and sugar were shown in Figure 4.9. Linear relationships between temperature and electrical conductivity were evident (R^2= 0.99-1) in all cases. This linear increasing trend agreed with those reported by several authors (Plaichoom, 2002; Marcotte *et al.*, 2000; Kanchanakitsakul, 1999; Yongsawatdigul *et al.*, 1995; Wang and Sastry, 1993; deAlwis and Fryer, 1992; Palaniappan and Sastry, 1991a,b; Halden *et al.*, 1990). The relationships were presented as regression parameters as equation 3.2 (Table 4.9). The positive value of temperature coefficients indicated the increase in

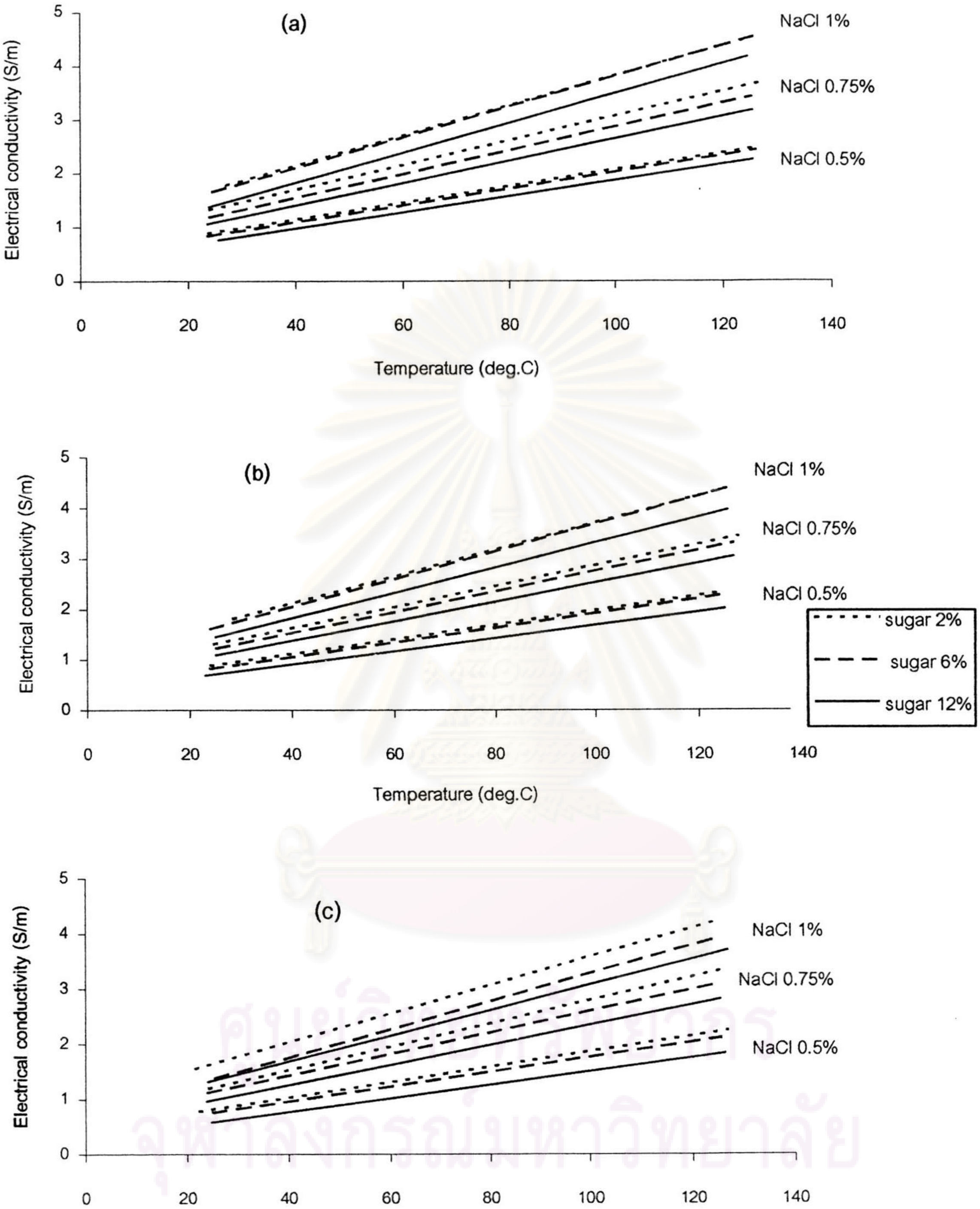

Figure 4.9 Effect of salt and sugar on electrical conductivity of starch paste
(a) 2% starch paste, (b) 4% starch paste, (c) 8% starch paste

Table 4.9 Means of estimated parameters of electrical conductivity of salt-starch-sugar combinations as a function of temperature

Salt (%)	Starch (%)	σ_{25} (S/m) Sugar(%) 2	σ_{25} (S/m) Sugar(%) 6	σ_{25} (S/m) Sugar(%) 12	$m\sigma_{25}$ (S/m°C) Sugar (%) 2	$m\sigma_{25}$ (S/m°C) Sugar (%) 6	$m\sigma_{25}$ (S/m°C) Sugar (%) 12
0.5	2	0.902±0.015	0.856±0.015	0.744±0.013	0.0154±0*	0.0153±0*	0.0149±0*
	4	0.898±0.013	0.830±0.197	0.722±0.006	0.0147±0*	0.0147±0*	0.0130±0*
	8	0.812±0.022	0.734±0.030	0.602±0.024	0.0143±0*	0.0135±0*	0.0126±0*
0.75	2	1.304±0.057	1.201±0.009	1.100±0.023	0.0232±0*	0.0218±0*	0.0205±0*
	4	1.328±0*	1.218±0.002	1.085±0.023	0.0211±0*	0.0204±0*	0.0192±0*
	8	1.211±0.014	1.118±0.019	0.988±0.021	0.0208±0*	0.0195±0*	0.0179±0*
1	2	1.710±0.033	1.658±0.021	1.415±0.027	0.0288±0.001	0.0292±0*	0.0274±0*
	4	1.710±0.018	1.628±0.032	1.430±0.054	0.0268±0*	0.0278±0*	0.0255±0*
	8	1.652±0.004	1.383±0.033	1.310±0.004	0.0262±0*	0.0252±0*	0.0233±0*

$\sigma = \sigma_{25} + m\sigma_{25} (T -25)$ (equation3.2)

* 0 indicates values less than 0.001

conductivity at high temperature. This may be due to the increasing in ionic mobility at high temperature (Palaniappan and Sastry, 1991a,b). The σ values were found to increase to more than double from 25°C to 125°C for all combinations e.g. from 0.902 to 2.442 S/m for 0.5%salt-2%starch-2%sugar combination and from 1.31 to 3.64 for 1%salt-8%starch-12%sugar.

In the combination of salt-sugar-starch system, the salt-sugar-starch interaction effects were reported in various means such as, its ability to compete water and hence reduce the water mobility, the sugar-starch interaction resulting in less plasticizing effect of the system, and the cation-starch interaction in the presence of salts resulting in an increase in volume of starch granule and viscosity (Bircan and Barringer, 1998; Beleia *et al.*, 1996; Sudhakar *et al.*, 1995a,b; Chinachoti *et al.*, 1991a,b). The reduction of water mobility in the presence of sucrose during gelatinization, was confirmed by Chinachoti *et al.* (1991a) who used the Nuclear Magnetic Resonance spectroscopy to observe the effect and found that water mobility were originally high but drastically decreased on gelatinization because of the increase fraction of trapped water when sucrose was added. Similar result was also found on the reduction of ion mobility due to salt addition to starch (Chinachoti *et al.*, 1991a). Therefore in the gelatinization step prior to ohmic heating, the water was partly trapped by starch and bound by sugar.

Among the salt-sugar-starch combinations, the lowest electrical conductivity was found in the mixture of 0.5% salt-12% sugar-8% starch. This mixture was the lowest salt and highest sugar and starch concentration within the study range. Whereas the highest electrical conductivity was found in the 1%salt-2%sugar-2% starch combination which was the highest salt and lowest sugar and starch. As the salt concentration increased from 0.5% to 1%, the relationship between electrical conductivity and temperature was increased in all starch-sugar combinations due to the increase in Na^+ and Cl^- for conducting electrical current. This effect of salt on σ agreed with those of Palaniappan and Sastry (1991a,b), Yongsawatdikul *et al.* (1995) and Marcotte *et al.* (2000). Increasing sugar from 2 to 12% caused the electrical conductivities of starch paste to decrease in most of the combinations, e.g. σ_{25} of 1.328, 1.218 and 1.085 S/m; $m\sigma_{25}$ of 0.0211, 0.0204 and 0.0192 S/m°C were found on 0.75%salt-4%starch with 2, 4, 12% sugar respectively.

These might be caused by a decrease in ionic mobility resulted from the sugar-water binding.

In the combination of salt-sugar-starch system, the complementary effect of decreasing in electrical conductivity by sugar and starch was found. This may be because water was bound by both starch and sugar. However, an increase in salt content would raise the σ and override the decreasing effect of sugar and starch. The salt content appeared to dictate the electrical conductivity of the combined system due to the increase in ionic content of the system. The decreasing of electrical conductivity by sucrose and starch as well as the increasing of electrical conductivity by salt in this study could be explained by the contribution of ionic content and ionic/water mobility.

From the data, a stepwise linear multivariate regression was used to correlate the electrical conductivity of system and temperature, salt, sucrose, and starch. It was found that the empirical correlation was ($R^2 = 0.994$):

$$\sigma = 0.379 + 0.871Sa - 0.0371St - 0.0298Su + 0.00164T + 0.0251SaT \ldots\ldots (4.1)$$

All variables were highly significant ($p \leq 0.001$). Only SaT interaction was found significant ($p \leq 0.05$). Apart from all main effects in the equation, the addition term of SaT indicated that an increase in electrical conductivity with temperature was greater at higher salt content. The equation was verified with the experiment and found that the model predicted well with 3% average error (Figure 4.10).

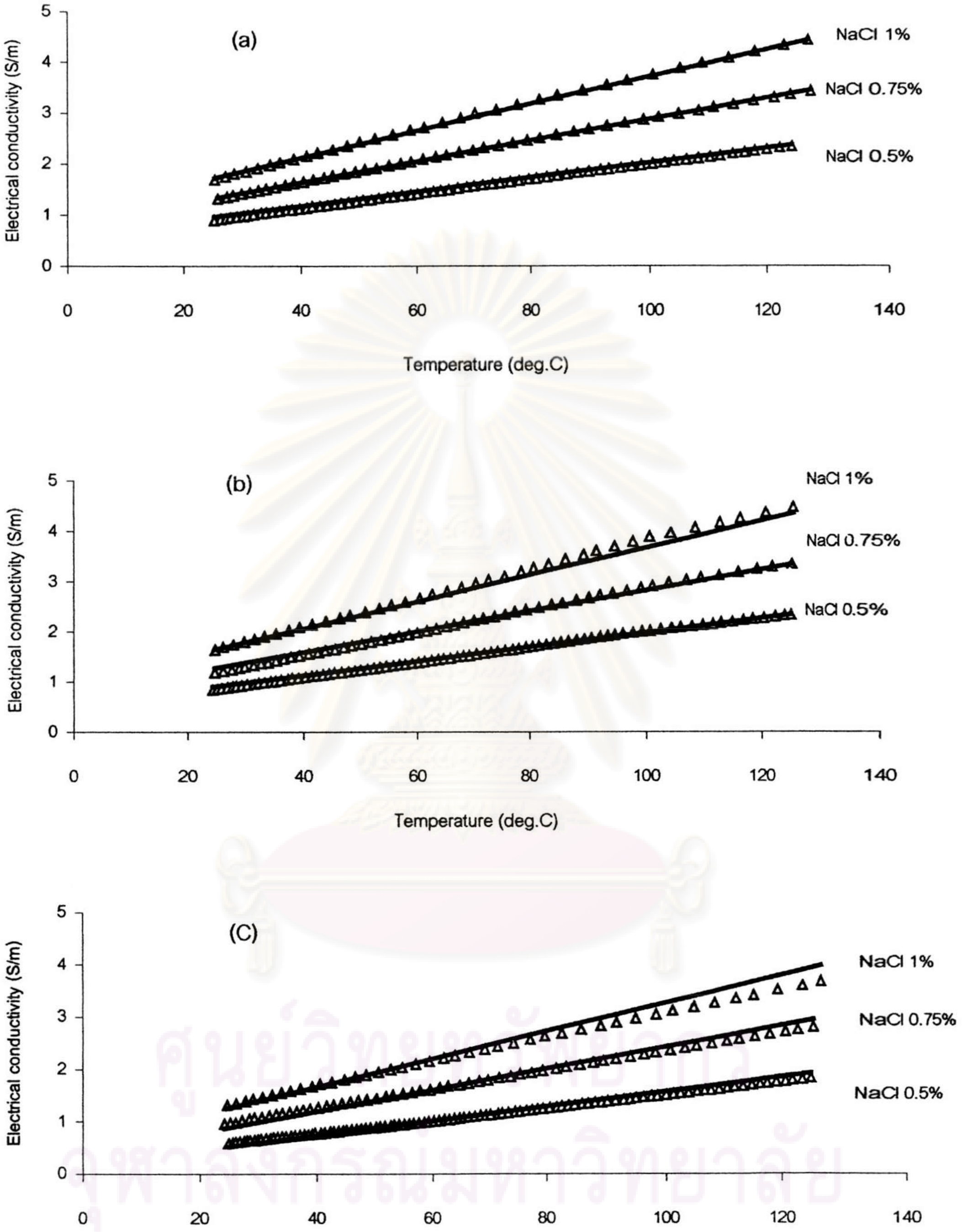

Figure 4.10 The change in electrical conductivity of starch paste with temperature (a) starch 4% + sugar2%, (b) starch 2% + sugar 6%, (c) starch 8% + sugar 12%, ____: predicted values, Δ:experimental values

4.5 Effective electrical conductivity of the solid-liquid mixture

4.5.1 Electrical conductivity of individual phases

The measured σ of individual components were shown in Table 4.10 and Figure 4.11. Conductivity ratios of solid to liquid at 25°C and 125°C were also shown in Table 4.10 as the ratio was not consistent along the temperature range. It was found that all components had high conductivity ratio at 125°C than 25°C which meant that the rate of conductivity change of solid was higher than that of liquid at high temperature. Among the samples studied, surimi had the highest σ, followed by the liquid (0.75% salt- 4% starch- 2% sugar), the salted white radish, salted potato, unsalted potato and unsalted white radish was the least conductive. Comparing to the σ of liquid, σ of surimi was relative higher because it contained 1% salt content which was higher than 0.75% salt in liquid. Both types of vegetable samples had much lower σ than that of liquid and the potato was slightly more conductive than white radish due to the original presence of ions in vegetable tissues. In salted vegetables, soaking in 0.75% salt overnight was performed in order to increase the ionic content within the vegetable issue. It was found that the salted white radish had higher σ than the salted potato even though the unsalted potato was more conductive than the unsalted white radish. This implied that more salt diffused into white radish tissue than in potato tissue. Difference in vegetable structure was considered to be the reason. As potato was rather starchy and dense compared to the fibrous structure of white radish, salt could diffuse into white radish more easily within the same soaking time resulting in higher σ. Therefore, the conductivity ratio of salted white radish was higher than that of salted potato, while it was lower in unsalted white radish than unsalted potato. It should be noted that the σ of salted vegetables would never reach that of salt solution at 0.75% since the moisture of the vegetable itself may diffuse out of the vegetable structure during equilibration and would dilute the salt concentration as soaking time increased. The variation in σ of vegetable samples between batches of study was also found due to the natural variation of non-homogenity of food structures. For vegetables, the variation could possibly be due to the distribution of vascular tissue (Palaniappan and Sastry,1991a; Wang and Sastry,1997b; Lima *et al.*,1999; Lima and Satry,1999; Fu and Hsieh,1999).

Table 4.10 Electrical conductivity equation and conductivity ratio of solid to liquid at 25°C and 125°C of individual phases

Materials	Equation	R^2	σ_{25}[a]	σ_{125}[b]	σ_s/σ_l[c] at 25°C	σ_s/σ_l at 125°C
Liquid*	$\sigma = 0.8041 + 0.0208T$	0.99	1.324	3.404	-	-
Unsalted potato	$\sigma = 0.1121 + 0.0118T$	0.98	0.407	1.587	0.31	0.47
Salted potato	$\sigma = 0.1863 + 0.0170T$	0.98	0.611	2.311	0.46	0.68
Unsalted white radish	$\sigma = 0.0364 + 0.0109T$	0.97	0.309	1.399	0.23	0.41
Salted white radish	$\sigma = 0.3880 + 0.0181T$	0.97	0.840	2.650	0.63	0.78
Surimi	$\sigma = 0.4968 + 0.0256T$	0.99	1.137	3.697	0.86	1.09

* 0.75% salt-2% sugar-4% starch

[a, b] σ at 25°C and 125°C

[c] conductivity ratio of solid to liquid

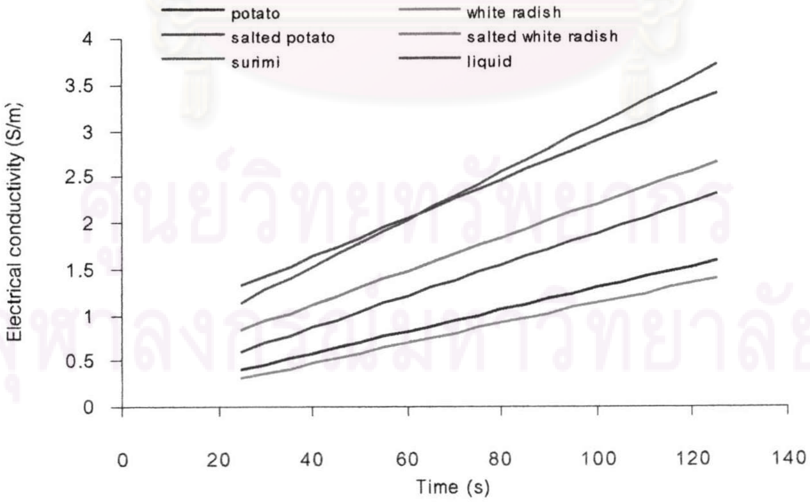

Figure 4.11 Mean electrical conductivity with temperature of individual components

4.5.2 Effective electrical conductivity

During ohmic heating of solid-liquid mixture, the voltage and current were measured and calculated as effective electrical conductivity.

4.5.2.1 Single-type solid in liquid

The relationship between σ_{eff} and liquid temperature of the single-type solid in liquid at volume fraction (vf) of 0.2, 0.4 and 0.6 compared to that of liquid alone was shown in Figure 4.12. The corresponded equations were tabulated in Table 4.11. It was found that the linear relationships were evident ($R^2 = 0.99$) for all mixtures. Upon heating, an increase in ionic mobility of foods existed (Plaichoom, 2002; Marcotte *et al.*, 2000; Kanchanakitsakul, 1999; Yongsawatdigul *et al.*,1995; Wang and Sastry, 1993; deAlwis and Fryer, 1992; Palaniappan and Sastry, 1991a,b; Halden *et al.*,1990). Ion exchanges between phases may possibly occur since the ionic contents were different.

From Figure 4.12, it was shown that the σ_{eff} -T curve of vegetable in liquid was lower than that of liquid alone in all cases. This was because all vegetables were less conductive than the liquid (Figure 4.11), hence the mixture of vegetable in liquid would have a lower value of σ compared to that of liquid. This result agreed with those reported by Palaniappan and Sastry (1991b), Kanchanakitsakul (1999), and Plaichoom (2002). On the other hand, surimi had higher σ than the liquid, thus the combination of surimi in liquid had higher σ. Increasing vf of solids gave higher difference between σ_{eff} of the mixture and of the liquid (Figure 4.11). This indicated that the σ_{eff} of the solid-liquid mixture depended on the σs of the components and the volume fraction of solids.

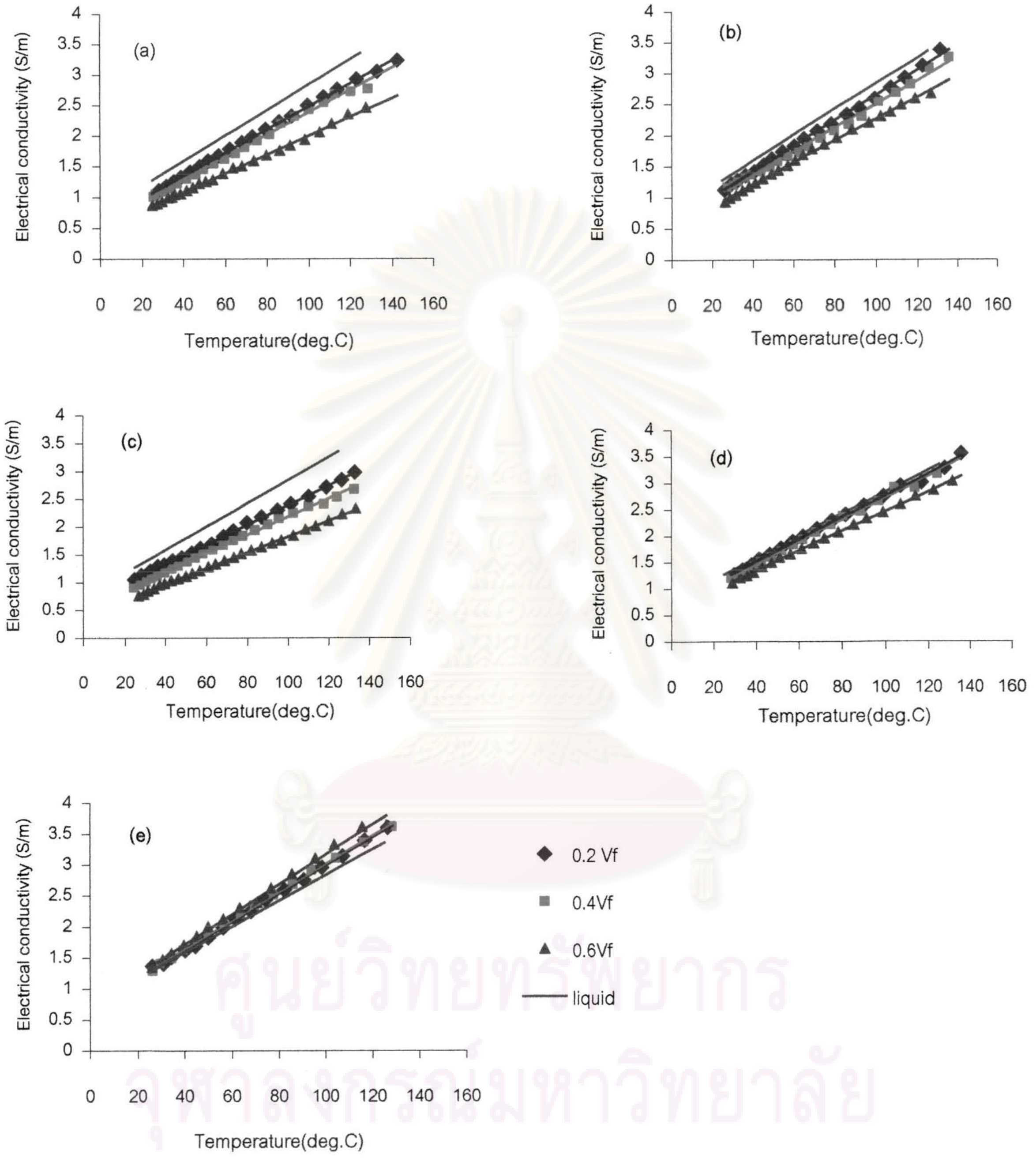

Figure 4.12 Effective electrical conductivity of single-type solid in 0.75% salt-2% sugar-4% starch liquid with various volume fraction
(a) unsalted potato, (b) salted potato, (c) unsalted white radish,
(d) salted white radish, (e) surimi

Table 4.11 Effective electrical conductivity equation of solid in liquid at various volume fractions ($R^2 = 0.99$)

Mixture	vf	Equation
Unsalted potato in liquid	0.2	$\sigma_{eff} = 0.607 + 0.0187T$
	0.4	$\sigma_{eff} = 0.549 + 0.0183T$
	0.6	$\sigma_{eff} = 0.469 + 0.0153T$
Salted potato in liquid	0.2	$\sigma_{eff} = 0.589 + 0.0206T$
	0.4	$\sigma_{eff} = 0.584 + 0.0192T$
	0.6	$\sigma_{eff} = 0.496 + 0.0179T$
Unsalted white radish in liquid	0.2	$\sigma_{eff} = 0.626 + 0.0176T$
	0.4	$\sigma_{eff} = 0.545 + 0.0164T$
	0.6	$\sigma_{eff} = 0.399 + 0.0143T$
Salted white radish in liquid	0.2	$\sigma_{eff} = 0.693 + 0.0207T$
	0.4	$\sigma_{eff} = 0.629 + 0.0209T$
	0.6	$\sigma_{eff} = 0.604 + 0.0186T$
Surimi in liquid	0.2	$\sigma_{eff} = 0.712 + 0.0228T$
	0.4	$\sigma_{eff} = 0.720 + 0.0229T$
	0.6	$\sigma_{eff} = 0.748 + 0.0242T$
Unsalted potato and white radish in liquid	0.2	$\sigma_{eff} = 0.630 + 0.0179T$
	0.4	$\sigma_{eff} = 0.617 + 0.0169T$
	0.6	$\sigma_{eff} = 0.386 + 0.0173T$
Unsalted potato and surimi in liquid	0.2	$\sigma_{eff} = 0.619 + 0.0214T$
	0.4	$\sigma_{eff} = 0.567 + 0.0215T$
	0.6	$\sigma_{eff} = 0.519 + 0.0192T$
Unsalted white radish and surimi in liquid	0.2	$\sigma_{eff} = 0.695 + 0.0212T$
	0.4	$\sigma_{eff} = 0.556 + 0.0212T$
	0.6	$\sigma_{eff} = 0.518 + 0.0204T$
Salted potato and white radish in liquid	0.2	$\sigma_{eff} = 0.624 + 0.0217T$
	0.4	$\sigma_{eff} = 0.594 + 0.0204T$
	0.6	$\sigma_{eff} = 0.617 + 0.0192T$
Salted potato and surimi in liquid	0.2	$\sigma_{eff} = 0.707 + 0.0217T$
	0.4	$\sigma_{eff} = 0.695 + 0.0228T$
	0.6	$\sigma_{eff} = 0.515 + 0.0256T$
Salted white radish and surimi in liquid	0.2	$\sigma_{eff} = 0.729 + 0.0222T$
	0.4	$\sigma_{eff} = 0.692 + 0.0232T$
	0.6	$\sigma_{eff} = 0.549 + 0.0239T$

Comparing between the salted and unsalted vegetables, It was found that the salted vegetables in liquid had higher σ_{eff} than the unsalted vegetables. The temperature coefficients of salted vegetables in liquid were 0.0206, 0.0192 and 0.0179 S/m°C for potato and 0.0207, 0.0209 and 0.0189 S/m°C for white radish compared to 0.0187, 0.0183 and 0.0153 S/m°C of unsalted potato in liquid and 0.0176, 0.0164 and 0.0143 S/m°C of unsalted white radish in liquid at 0.2, 0.4 and 0.6 vf (Table 4.11). This was due to the higher ionic content in salted solid resulted in higher σ than the unsalted solid (Wang and Sastry, 1993).

Comparing potato to white radish, increasing vf from 0.2 to 0.6 gave high decreasing in σ_{eff} of unsalted white radish-liquid system than the unsalted potato-liquid system which was due to the lower conductivity ratio of unsalted white radish compared to the unsalted potato. On the other hand, increasing vf from 0.2 to 0.6 resulted in higher lowering effect in salted potato than salted white radish due to the lower conductivity ratio of salted potato than salted white radish.

4.5.2.2 Two-type solids in liquid

The results of σ_{eff}–T curves as well as the influence of volume fraction of solids in liquid were shown in Table 4.11 and Figure 4.13. Similar to the single-type solid in liquid, all mixtures had linear relationships between σ and temperature ($R^2 = 0.99$). Increasing in solid fraction gave the lower σ_{eff} in all mixtures except the salted vegetables and surimi (Figure 4.13 e,f) which was corresponded to the σs of individual phases (Figure 4.11). In the mixture of vegetable in liquid, increasing the volume fraction of vegetable indicated an increase in lower conductive phase relative to the liquid which resulted in lower σ_{eff} of the system. These results agreed with that of Kanchanakitsakul (1999) which reported that the σ_{eff} of multi-component mixtures of vegetable solids in salt solution decreased as the volume fraction of vegetables increased and Palanaippan and Sastry (1991c) for potato in sodium phosphate solution.

In the mixture of vegetable and surimi in liquid, the σ_{eff} would mainly depend on the combination of σ of apparently higher than liquid (surimi) and much lower than liquid (vegetable) with equal fractions. Unsalted vegetables had relative lower conductivity ratio than salted vegetables, thus gave lower σ_{eff} while salted

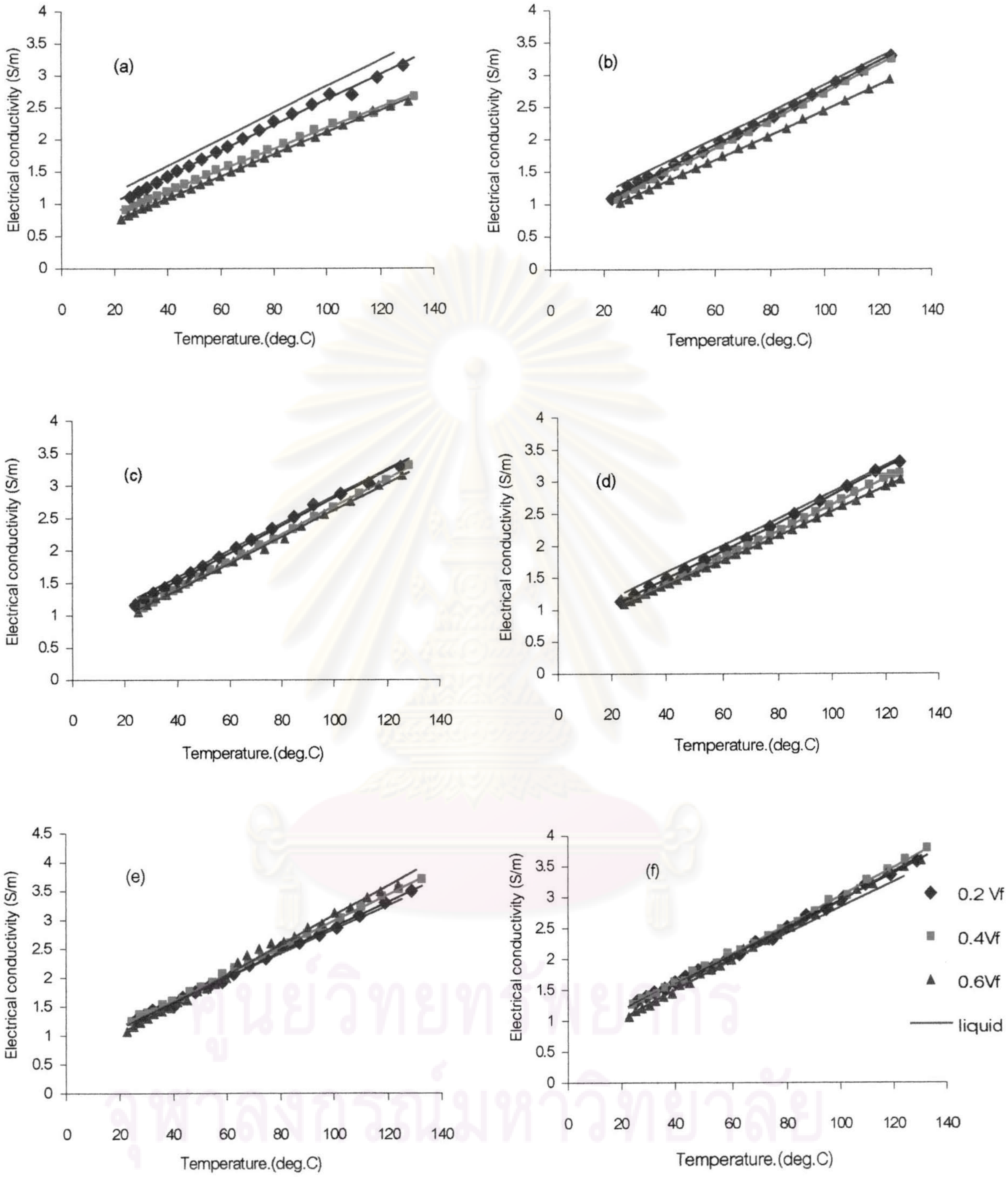

Figure 4.13 Effective electrical conductivity of two-type solids in 0.75% salt-2% sugar-4% starch liquid with various volume fraction
(a) unsalted potato and white radish, (b) unsalted potato and surimi,
(c) unsalted white radish and surimi, (d) salted potato and salted white radish
(e) salted potato and surimi, (f) salted white radish and surimi

vegetables gave higher σ_{eff} than the liquid when mixed with surimi. Comparing potato to white radish in the mixture with surimi in liquid, the mixture with salted potato gave lower σ_{eff} than that of salted white radish while the mixture with unsalted potato gave higher σ_{eff} than that of unsalted white radish which could be explained by the conductivity of the individual phases. However, the σ_{eff} of the vegetable and surimi mixture were found to be higher than those of the mixtures of vegetables.

From the mixture of two-type solids in liquid, it was found that the σ_{eff} of the mixture depended on the σ and vf of each component. In the mixture of solids with higher and lower σ than that of liquid with equal fraction, the conductivity ratio dictated the trend of σ_{eff}.

4.6 Prediction of effective electrical conductivity of solid-liquid mixture

Base on the circuit-analogy approach, the σ of solids from equations in Table 4.10 and σ of liquid calculated from equation 4.1 were used to estimate the σ_{eff} of solid-liquid mixture using equation 2.12-2.26. The predicted σ_{eff} equations and the difference ranges compared to those obtained from experiment were shown in Table 4.12 and the σ_{eff} –T curves were shown in Figure 4.14 to 4.15. From Table 4.12 the calculated σ_{eff} compared to those obtained from the experiments agreed well within ±10% difference for almost all mixtures (Appendix D). This indicated that the circuit-analogy approach could be effectively used to estimate the σ_{eff} of multi-component mixtures within satisfactory agreement. The results agreed with the σ_{eff} of vegetables in salt solution at 0.2-0.6vf reported by Kanchanakitsakul (1999).

It was noticed that high errors were obtained at 0.6 vf in most combinations. These might be due to the fact that high concentration of solids did not comply to the assumption for the calculation. As the circuit concept assumed that both phases equivalent to the three resistances: liquid in parallel and series, and solid in parallel, the packing of a large amount of solid cubes in liquid may not follow the arranged patterns. The chances of solid cubes attached to each other were possibly found and would directly influence the calculation. Therefore, this approach may have the limitation to the system of very high amount of solids which was not often found in commercial practice. It should be noted that the error for σ_{eff} calculation had included the error of liquid conductivity estimation as well.

Table 4.12 Equations predicting effective electrical conductivity of solid-liquid mixtures during ohmic heating from 25-125°C

Mixture	vf	Equation	Difference range (%)
Unsalted potato in liquid	0.2	$\sigma_{eff} = 0.678 + 0.0187T$	2.4 - 6.6
	0.4	$\sigma_{eff} = 0.532 + 0.0170T$	-4.9 - (-6.3)
	0.6	$\sigma_{eff} = 0.396 + 0.0153T$	-3.0 - (-8.5)
Salted potato in liquid	0.2	$\sigma_{eff} = 0.634 + 0.0201T$	-0.5 - 2.9
	0.4	$\sigma_{eff} = 0.511 + 0.0194T$	2.5 - 5.1
	0.6	$\sigma_{eff} = 0.395 + 0.0187T$	-0.04 - (-8.6)
Unsalted white radish in liquid	0.2	$\sigma_{eff} = 0.651 + 0.0184T$	4.2 - 4.4
	0.4	$\sigma_{eff} = 0.478 + 0.0163T$	-3 - (-7.3)
	0.6	$\sigma_{eff} = 0.32 + 0.0143T$	-3.6 - (-10.5)
Salted white radish in liquid	0.2	$\sigma_{eff} = 0.734 + 0.0201T$	-1.0 - 2.0
	0.4	$\sigma_{eff} = 0.643 + 0.0197T$	-1.4 - (-4.2)
	0.6	$\sigma_{eff} = 0.556 + 0.0193T$	-3.0 - 1.2
Surimi in liquid	0.2	$\sigma_{eff} = 0.768 + 0.0217T$	1.6 - 2.9
	0.4	$\sigma_{eff} = 0.712 + 0.0229T$	-0.1 - 0.8
	0.6	$\sigma_{eff} = 0.656 + 0.0241T$	-3.1 - 1.0
Unsalted potato and white radish in liquid	0.2	$\sigma_{eff} = 0.648 + 0.0193T$	-1.8 - 0.2
	0.4	$\sigma_{eff} = 0.472 + 0.0180T$	-0.3 - (-11.3)
	0.6	$\sigma_{eff} = 0.310 + 0.0168T$	-5.1 - (-9.8)
Unsalted potato and surimi in liquid	0.2	$\sigma_{eff} = 0.719 + 0.0210T$	1.5 - 7.7
	0.4	$\sigma_{eff} = 0.613 + 0.0215T$	1.4 - 4.2
	0.6	$\sigma_{eff} = 0.511 + 0.0220T$	-0.3 - (-2.0)
Unsalted white radish and surimi in liquid	0.2	$\sigma_{eff} = 0.712 + 0.0210T$	-0.2 - 1.0
	0.4	$\sigma_{eff} = 0.600 + 0.0215T$	2.5 - 4.8
	0.6	$\sigma_{eff} = 0.492 + 0.0219T$	-4.4 - 3.2
Salted potato and white radish in liquid	0.2	$\sigma_{eff} = 0.725 + 0.0208T$	-0.3 - 6.7
	0.4	$\sigma_{eff} = 0.626 + 0.0211T$	3.7 - 4.2
	0.6	$\sigma_{eff} = 0.500 + 0.0214T$	-2.8 - 6.2
Salted potato and surimi in liquid	0.2	$\sigma_{eff} = 0.738 + 0.0216T$	-2.2 - (-0.5)
	0.4	$\sigma_{eff} = 0.652 + 0.0228T$	1.2 - 3.5
	0.6	$\sigma_{eff} = 0.567 + 0.0239T$	-0.8 - 4.3
Salted white radish and surimi in liquid	0.2	$\sigma_{eff} = 0.765 + 0.0218T$	-1.9 - 0.4
	0.4	$\sigma_{eff} = 0.705 + 0.0230T$	-0.6 - 0.3
	0.6	$\sigma_{eff} = 0.645 + 0.0243T$	-9.2 - (-4.0)

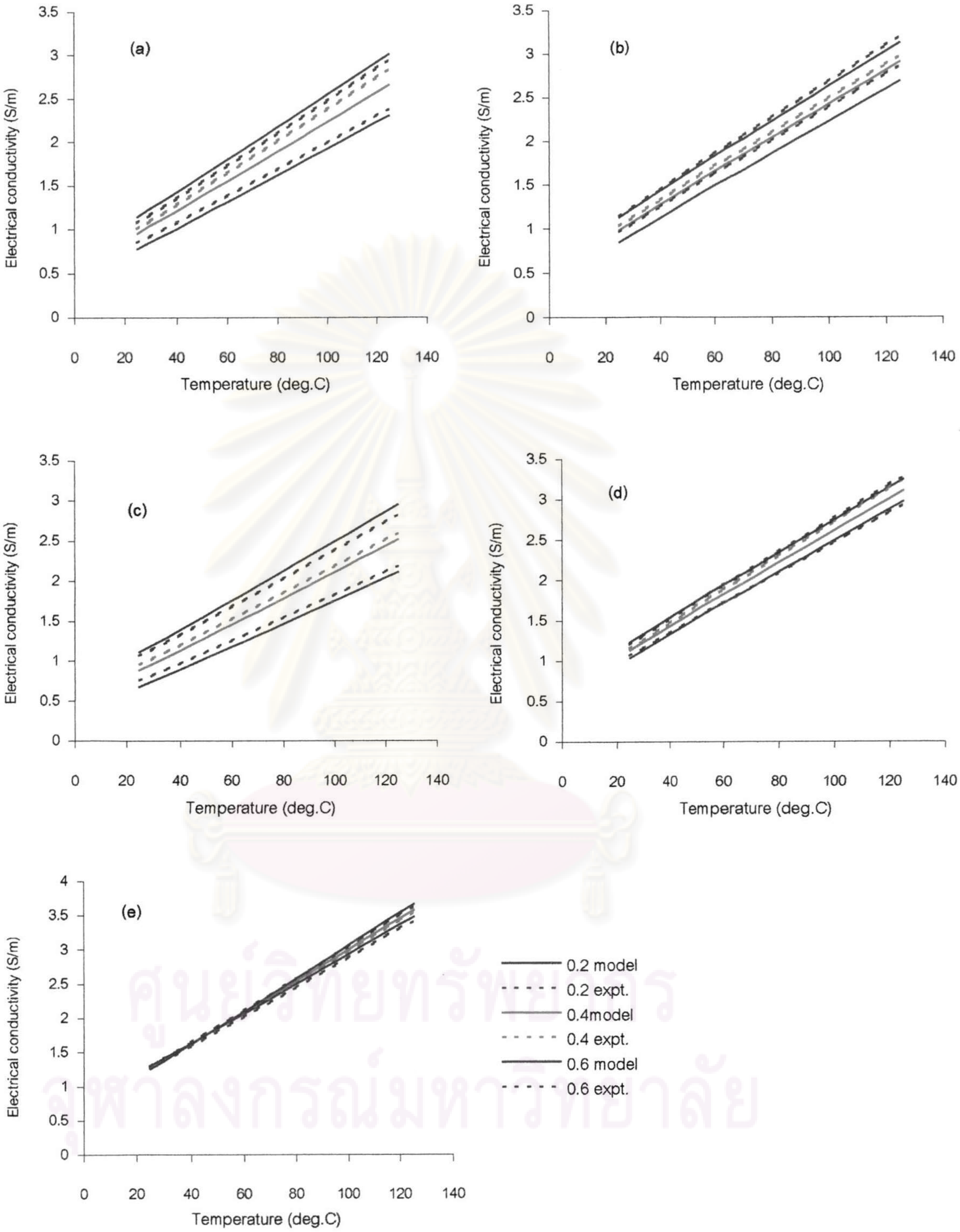

Figure 4.14 Effective electrical conductivity of single-type solid in liquid mixture at various volume fractions (a) unsalted potato, (b) salted potato, (c) unsalted white radish, (d) salted white radish, (e) surimi

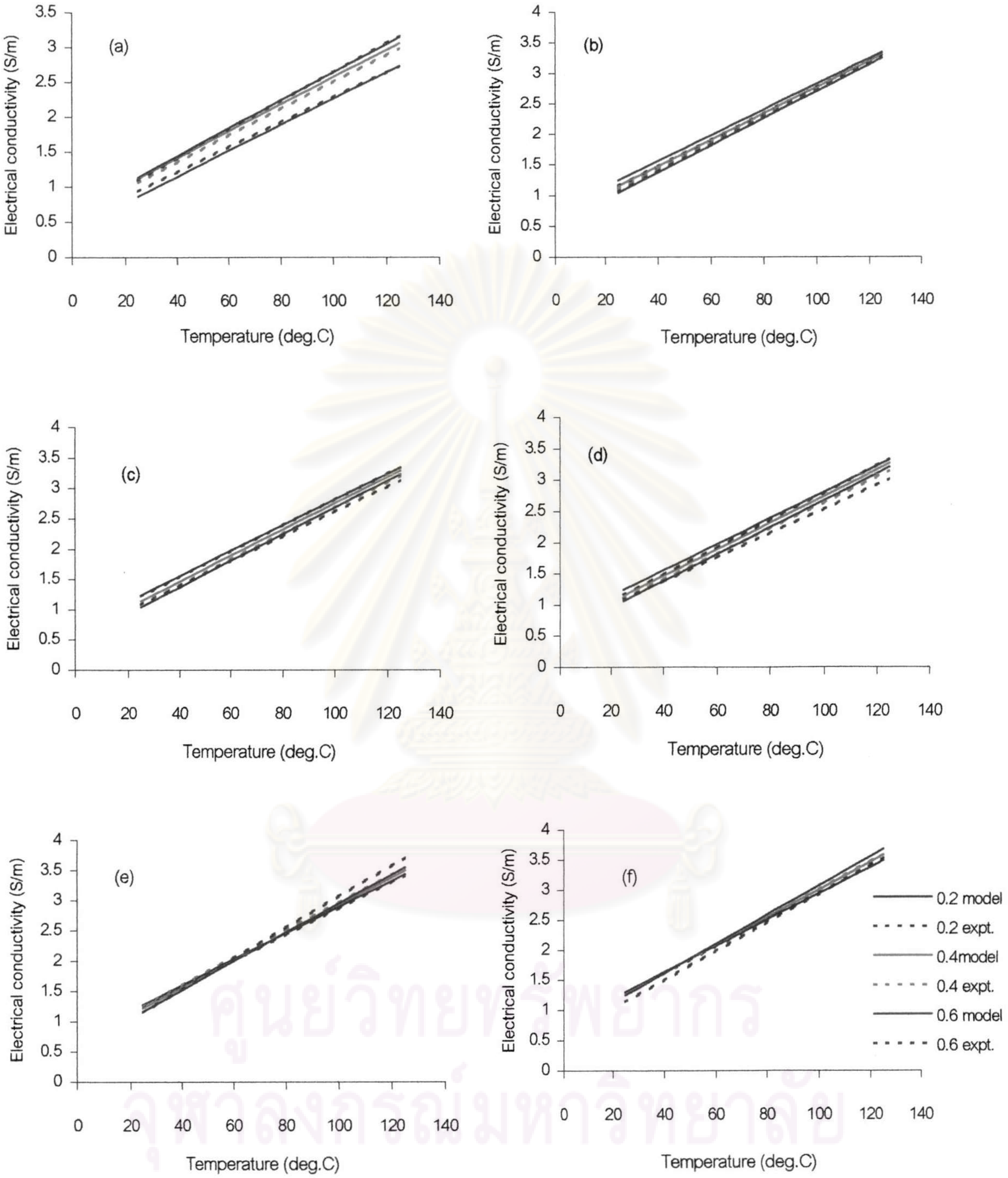

Figure 4.15 Effective electrical conductivity of two-type solids in liquid mixture at various volume fractions (a) unsalted potato and white radish, (b) unsalted potato and surimi, (c) unsalted white radish and surimi, (d) salted potato and salted white radish (e) salted potato and surimi, (f) salted white radish and surimi

4.7 Temperature prediction from the developed mathematical model

The mathematical model developed in this study (equation 2.30) was generated by assuming that the small solid cubes were uniformly distributed in the liquid like a homogeneous system. As the solid and the entire mixture were found to be heated at similar rate, the predicted temperatures were compared with the measured temperatures for 5 combinations of single-type solid in liquid and 6 combinations of two-type solids in liquid at 0.2, 0.4, and 0.6 vf.

4.7.1 Single-type solid in liquid

The heating profiles of liquid and solid in the mixture as well as the heating curves calculated from the model (Appendix F) for unsalted potato, salted potato, unsalted white radish, salted white radish, and surimi with various solid fraction were shown in Figures 4.16 to 4.20, respectively. Additional heating profile curve of liquid alone conducted at the same voltage gradient was overlaid on the same graph in order to compare the heating rate. It was found that the liquid and solid were heated at similar rates with the temperature difference not more than 10°C in most cases (Appendix E). It was interesting to note that vegetables which were the low conductive particles could heat as fast as the high conductive liquid. This agreed with Sastry and Palaniappan (1991a) who found that the low conductive potato particle could heat as fast as the salt solution at volume fraction of 0.23 due to the restriction of parallel conduction paths through the fluid. Therefore, it was justified to consider the mixture of small solid cubes in the liquid as a homogeneous system by assuming the population behavior as 'average' particles distribution in the developed mathematical model (Sastry and Palaniappan, 1992a). Thus the σ_{eff} was used to calculate the energy generation or mean power consumption which converted to the thermal energy of the entire mixture. Then the temperature was calculated using average thermophysical properties. So this model was simple and less computing time compared to the previous models which predicted each phase separately using complex calculation (deAlwis and Fryer, 1990; Palaniappan and Sastry, 1991a; Fryer *et. al.*, 1993; Fu and Hsieh, 1999).

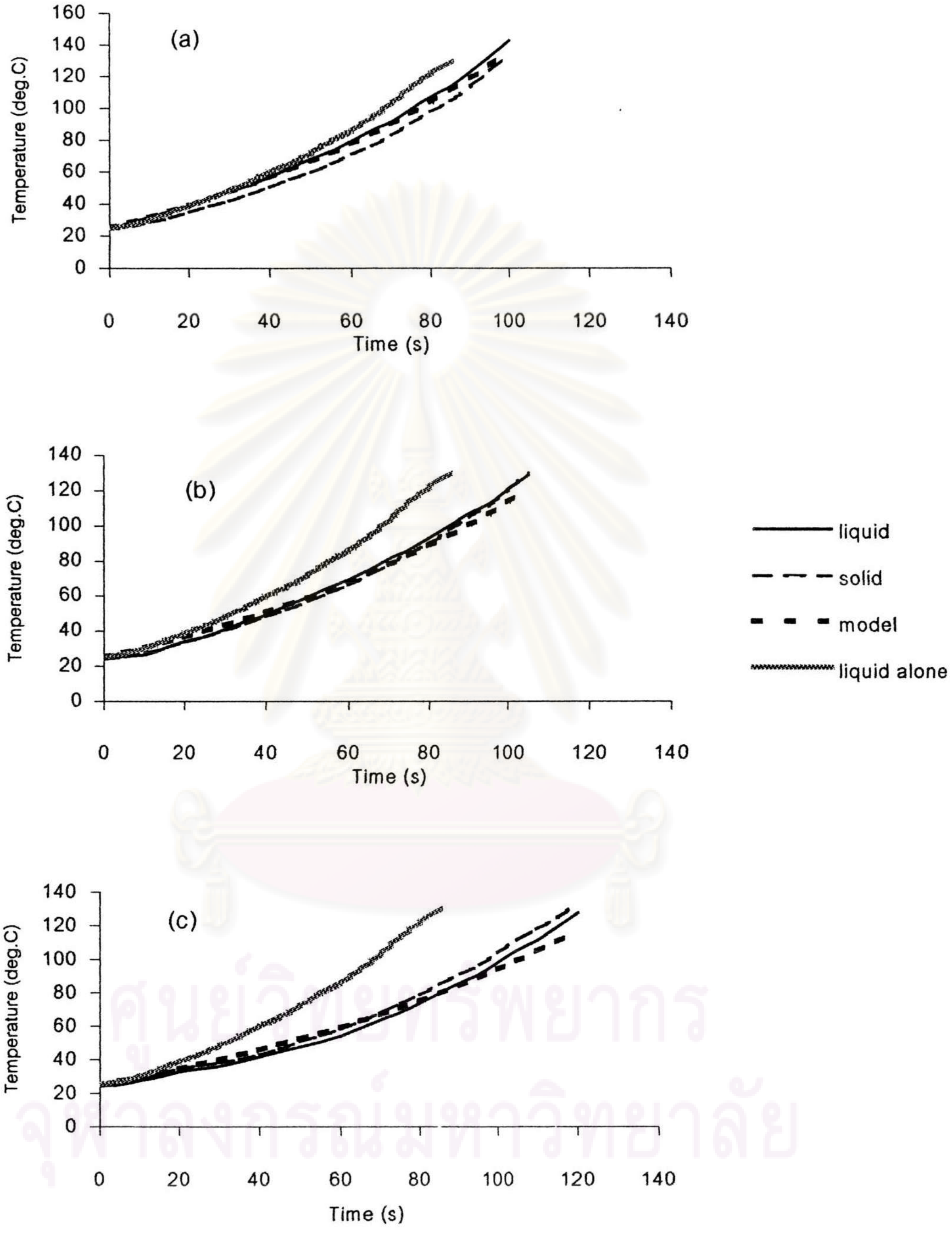

Figure 4.16 Temperature changes of unsalted potato in 0.75% salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

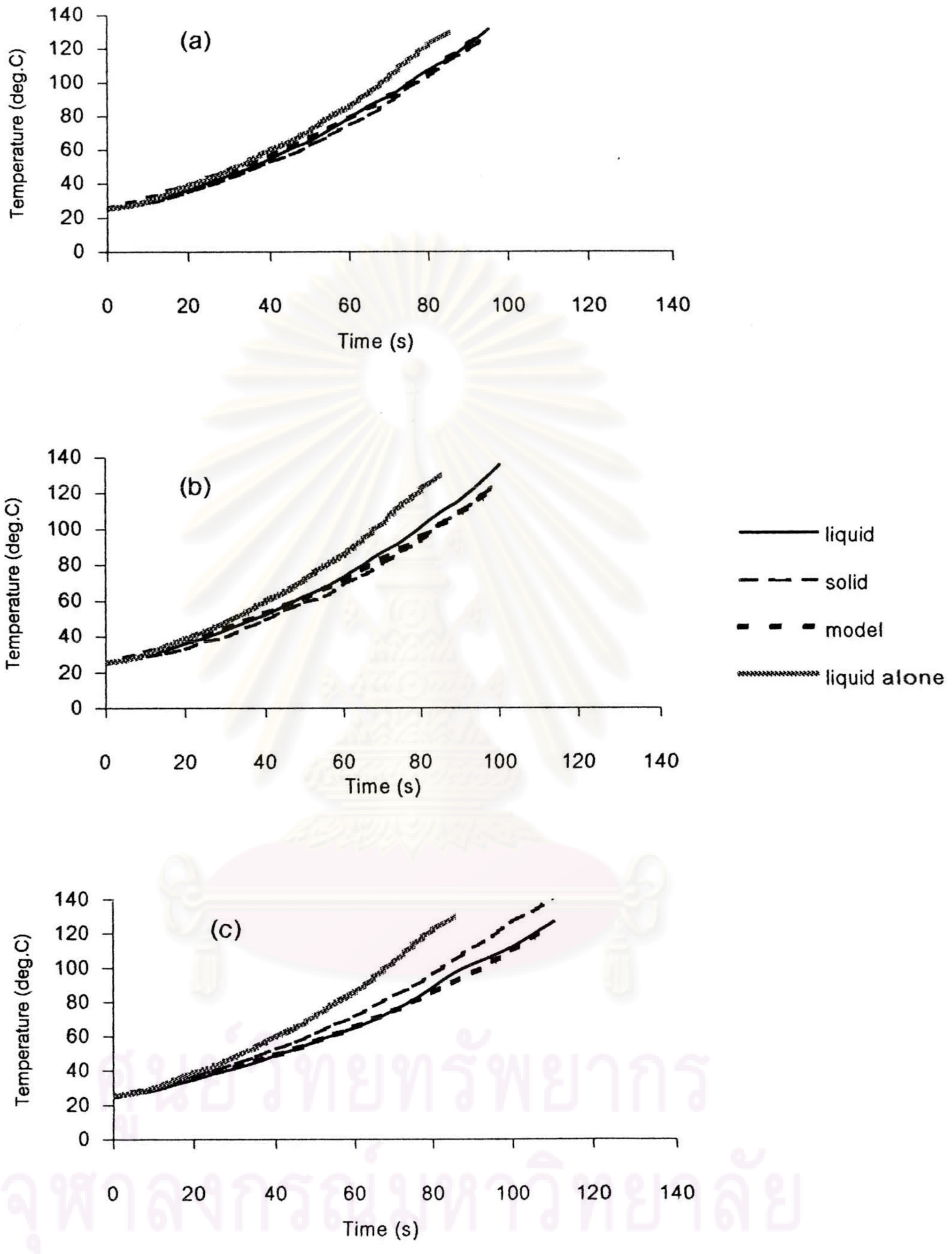

Figure 4.17 Temperature changes of salted potato in 0.75% salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

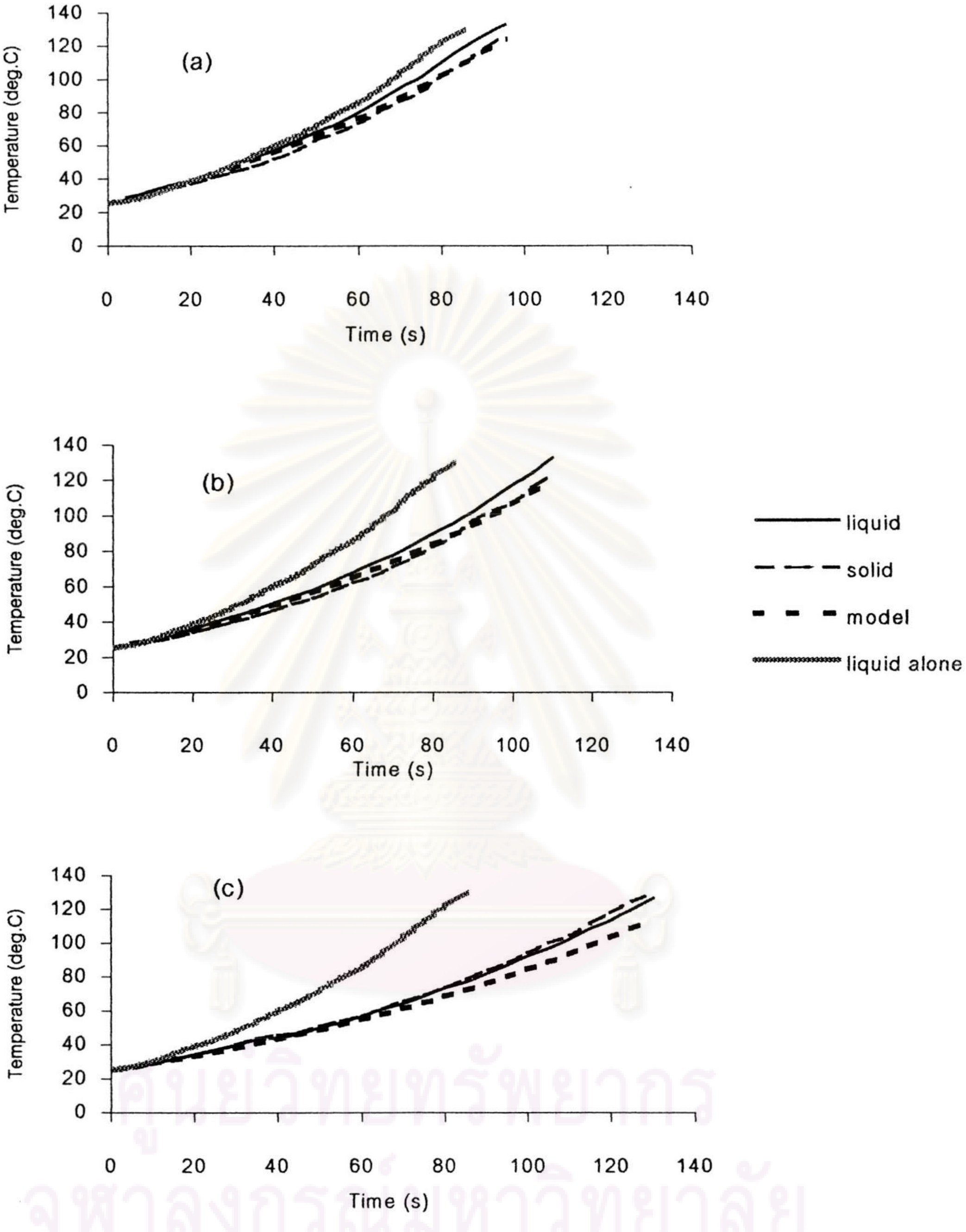

Figure 4.18 Temperature changes of unsalted white radish in 0.75% salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

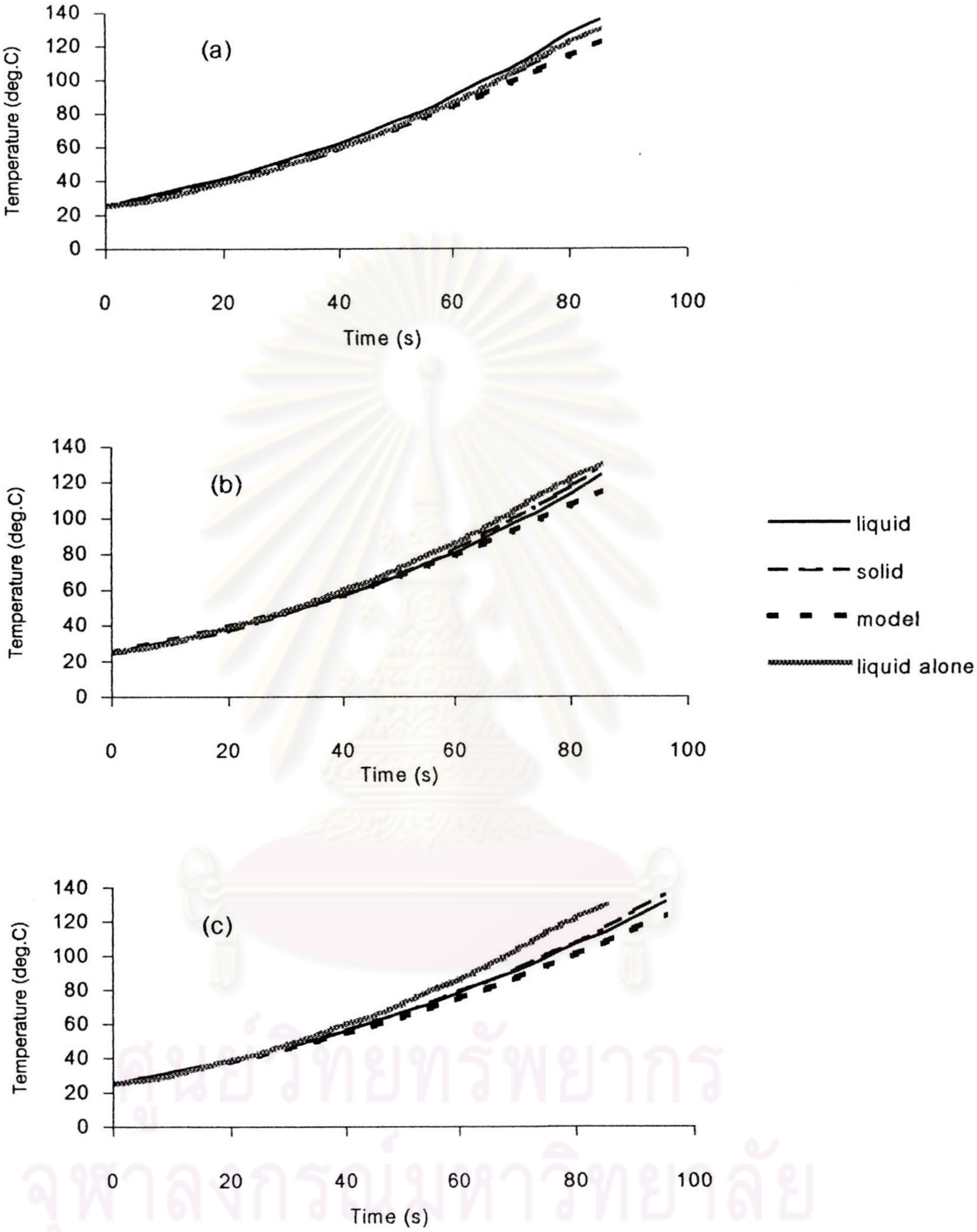

Figure 4.19 Temperature changes of salted white radish in 0.75% salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

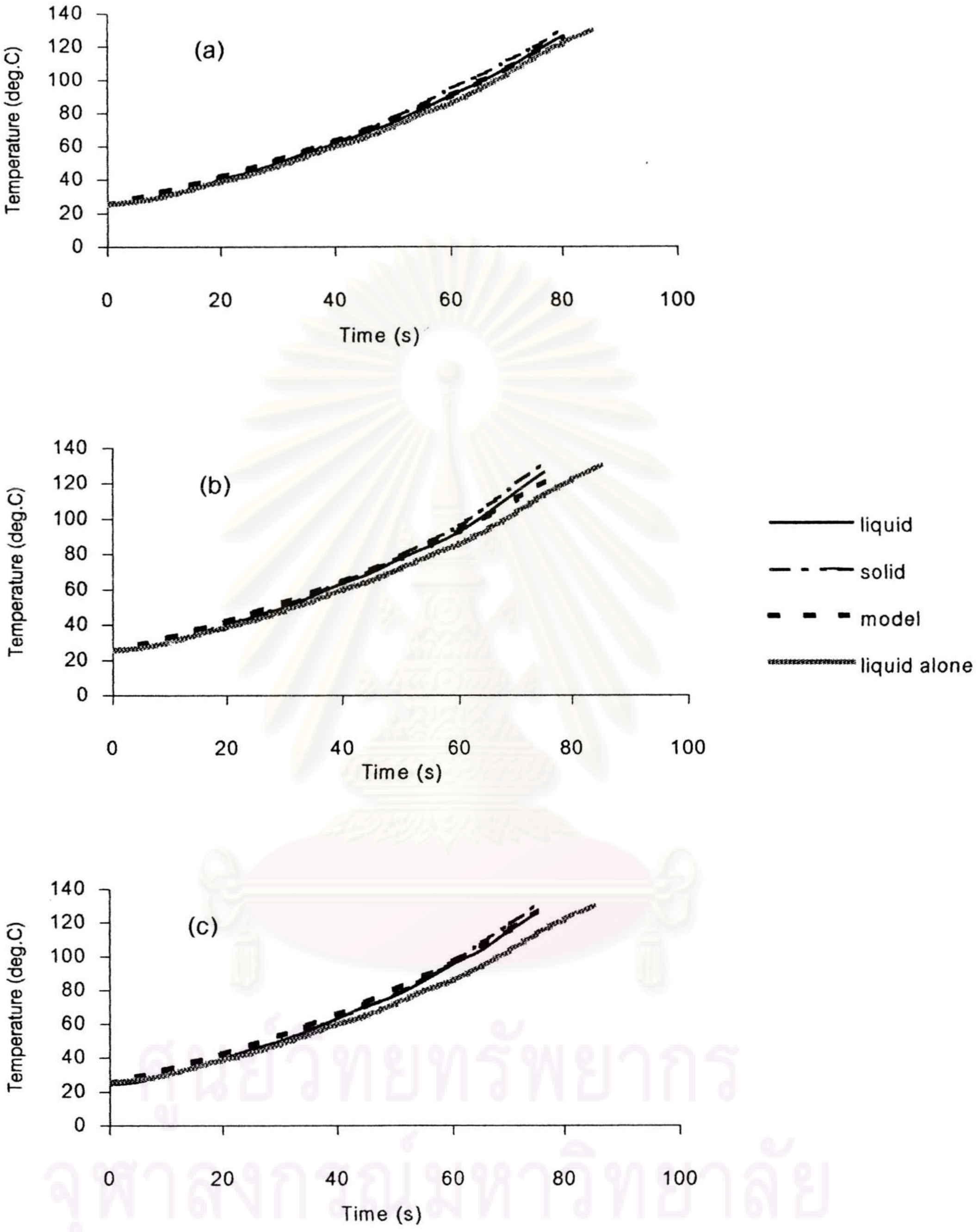

Figure 4.20 Temperature changes of surimi in 0.75% salt-2% sugar-4% starch liquid at various volume fractions (a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

Since the sterilization process needed to ensure satisfactory commercial sterility, the predicted temperature was thus compared with the slowest heating phase (Figures 4.16 - 4.20). It was found that the model gave a very good fitting for most of the experimental temperatures. In general, satisfactory agreement was obtained with the error ± 11 % in most cases. Among five mixtures with three vf studied, thirteen out of fifteen cases were found to predict temperature lower than the slowest heating phases and two cases were found to be overprediction. However, the underprediction was not consistent along the temperature range of 25-125°C. In most cases, small overprediction during 25-70°C were found but it turned to be underprediction when temperature was higher than 70°C (Tables E1-E5 in Appendix E). Since lethality would be significantly accounted for sterilizing at relative high temperature, thus the results in this study would show sufficient prediction. High error was obtained at high vf which corresponded to the error arisen from σ_{eff} calculation as mentioned in section 4.6. The two exceptions out of fifteen cases which overpredicted were the unsalted and salted potato mixture at 0.2 vf. The differences between the model and the potato particle temperature were not consistent along the temperature range, i.e. it increased up to about 10-13% as solid temperatures increased from 25 to 40°C and then decreased to about 2% at the end of heating (Figures 4.16 and 4.17a and Tables E1 and E2 in Appendix E). These indicated that the model predicted more closer to the solid temperature upon heating. The possible error for overprediction in these cases might be due to the temperature dependence of C_p of potato which was ignored in the calculation. Rice *et. al* (1988) reported the temperature dependence C_p of potato as shown in equation 2.10. The C_p of potato was significantly higher at high temperature, e.g. 2.735 and 4.015 kJ/kg°C at 40 and 90°C which indicated the slower temperature rise upon heating. However, the overprediction was not found at high vf even though the effect due to C_p variation should be pronounced. This was because at high vf, the error may counteract with the underestimated σ_{eff} and resulted in satisfactory agreement.

It was also found that in vegetable mixtures (Figures 4.16- 4.19), the experimental heating rate of both phases were slower than the heating curve of liquid alone and the salted mixture heated faster than the unsalted one while in surimi mixture, both solid and liquid heated faster than the liquid alone (Figure 4.20). The temperature differences between both phases and liquid alone were higher as the volume fraction increased. These corresponded to the σ_{eff} as presented in section 4.5 and 4.6. For the vegetable mixture at 0.2 vf , the vegetable particles heated slower than the liquid while that at 0.6 vf the liquid heated slower than the particle in all cases (Figure 4.16- 4.19). This indicated that increasing the vf from 0.2 to 0.6, the slowest heating phase changed from particle to liquid. This was possibly due to the fact that at high concentration, the low conductive phase represented the major resistant part and hence the parallel conduction paths for the current to pass through the liquid were restricted and forced a greater proportion of the total current to flow through the particles. These resulted in higher energy generation rate within the particles and consequently a greater relative heating rate. The phenomenon was consistent with that of Sastry and Palaniappan (1992a) which reported that increasing the potato volume fraction from 0.23 to 0.345, the particles heated faster even though the salt solution had a considerably higher conductivity. Similar point was found from the studies of de Alwis and Fryer (1990) with respect to orientation of a long thin particle in an electric field. If the particle was oriented across the current, it tended to 'block' the current, then the particle interior heated faster than the fluid.

4.7.2 Two-type solids in liquid

The predicted temperature profiles were compared with the measured temperature profiles for two-type solids in liquid (Figures 4.21 - 4.26) and corresponding data was provided in Table E6-E11 (Appendix E). In most cases the predictions were consistent with experimental data within ± 11 % error. The exceptions were the mixtures of liquid with unsalted potato and surimi at 0.4 vf (Figure 4.22b) and salted potato and salted white radish at 0.4 vf (Figure 4.24b) which were about 13% overprediction and that of unsalted white radish and surimi at 0.6vf (Figure 4.23c) which was about 13% underprediction. In the mixture of two-type solids in liquid, the heating profile of the entire mixture was of comparable heating rate and corresponded to the σ_{eff}. The solids heated slightly faster than the liquid in most cases. Interestingly, the vegetables either unsalted (Figure 4.21) or salted (Figure 4.24) could heat faster than the liquid at all volume fractions. Both vegetables were of similar heating rate and slightly higher than the liquid at all volume fractions. For the mixture of vegetables, either potato or white radish, with surimi in liquid (Figure 4.22-4.23), the surimi heated faster than the vegetable and liquid in all cases due to the high σ of surimi itself.

As the temperature behavior of multi-component mixtures could not be clearly explained, the error of prediction might be due to many factors. The heat transfer between components could have been occurred in real situation (deAlwis and Fryer, 1990; Palaniappan and Sastry, 1991a; Sastry and Palaniappan, 1992a,c; Fryer *et. al.*, 1993; Fu and Hsieh, 1999). The σ ratio of solid components, the σ distribution (from the three different components) within the mixture, and the ions diffusion may contribute for the heating behaviors (deAlwis and Fryer, 1990; Palaniappan and Sastry, 1991a; Sastry and Palaniappan, 1992c; Fryer *et. al.*, 1993; Fu and Hsieh, 1999). The temperature-dependence of physical properties of material had proven to be significant effects (Rice *et. al*, 1988; Sweat, 1986). It should also be noted that as the estimated values of liquid σ and σ_{eff} were used in temperature prediction, thus the errors of both predictions were contributed in the error of temperature prediction. Therefore, even though some overprediction was found from the model, within ±11% difference could be of satisfactory agreement compared to those obtained in other models (section 2.4.3) (deAlwis and Fryer, 1990; Sastry and Palaniappan, 1992a; Fryer *et. al.*, 1993; Fu and Hsieh, 1999). Further researches should be investigated for causes of the variation.

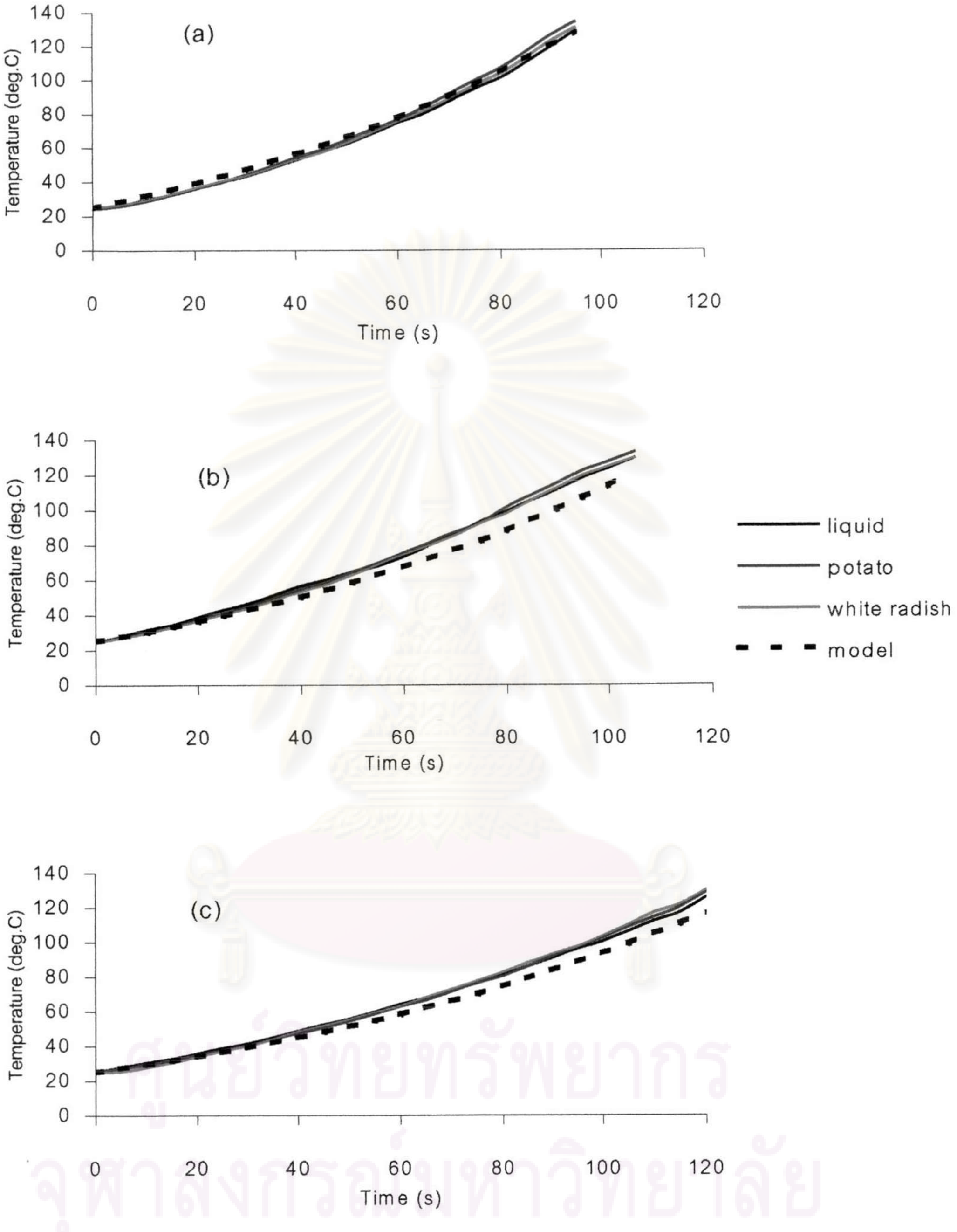

Figure 4.21 Temperature changes of unsalted potato and white radish in 0.75% salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

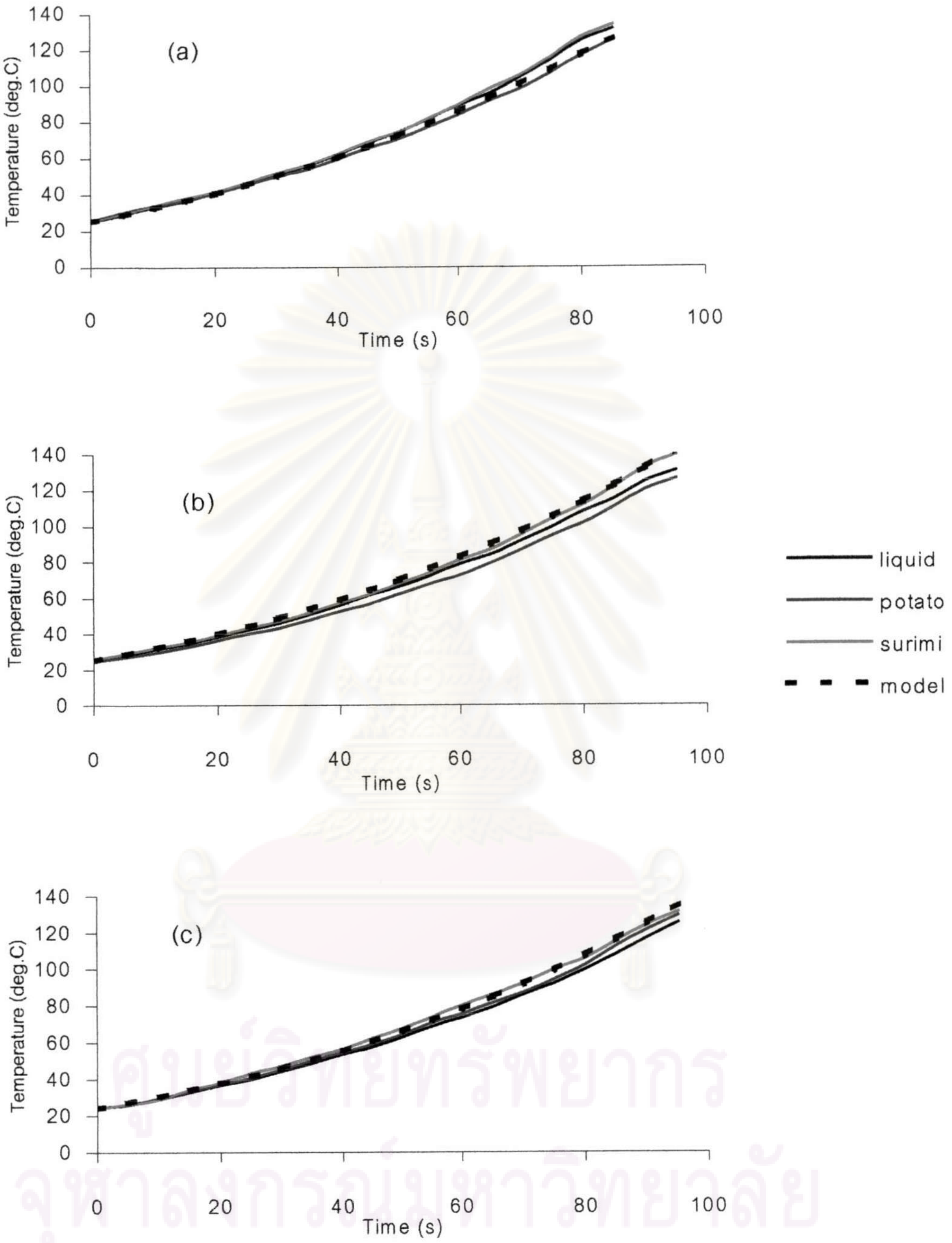

Figure 4.22 Temperature changes of unsalted potato and surimi in 0.75% salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

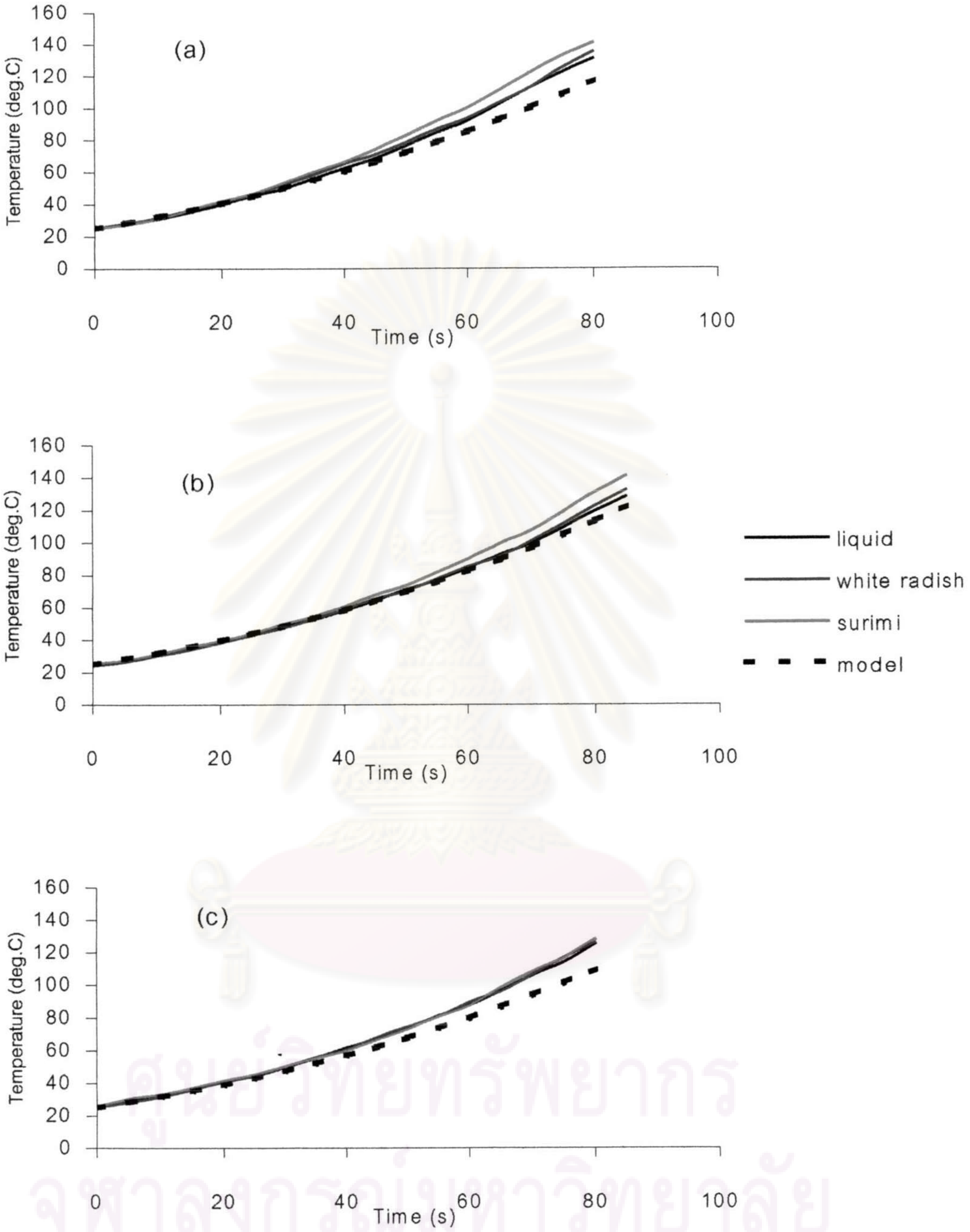

Figure 4.23 Temperature changes of unsalted white radish and surimi in 0.75% salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

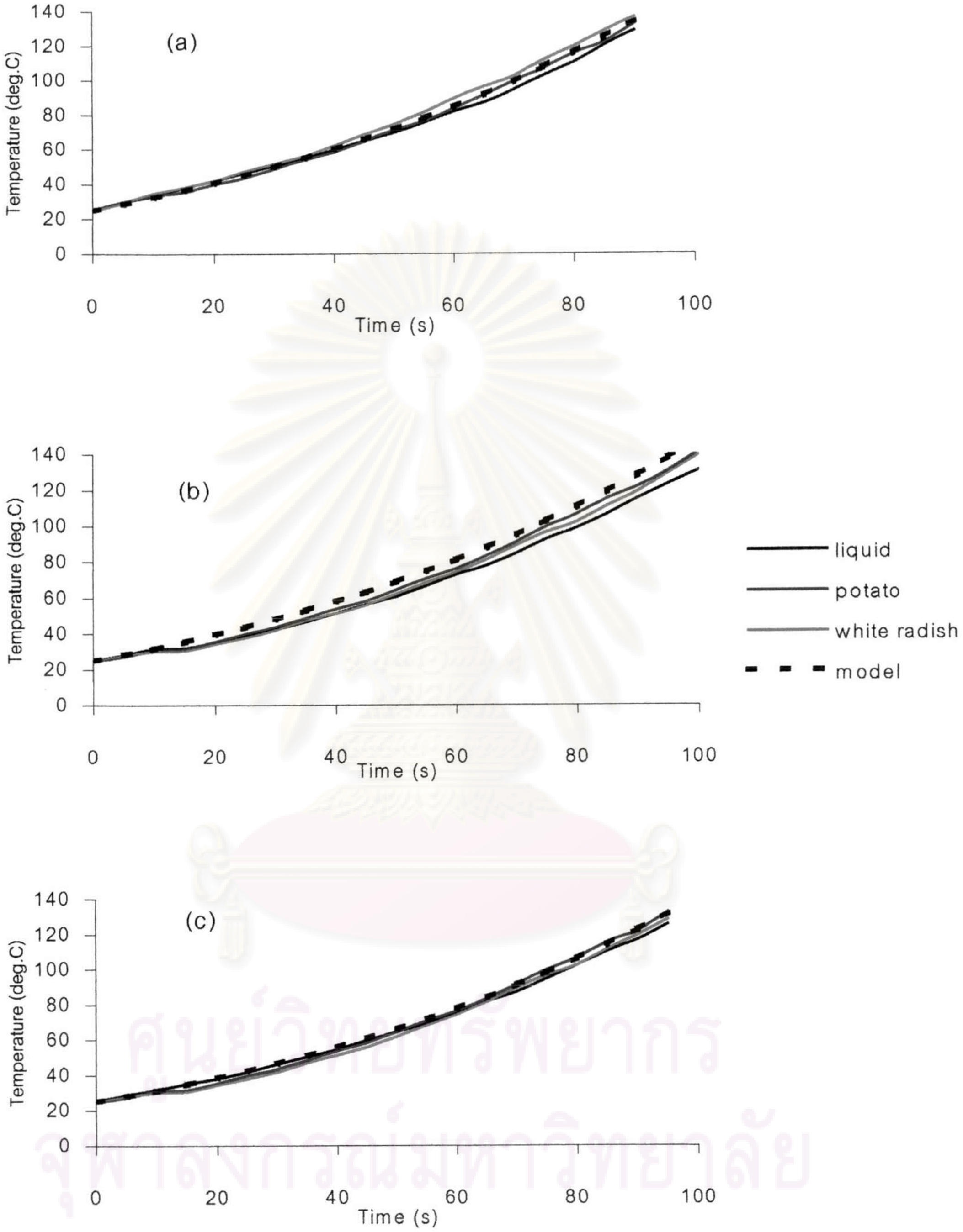

Figure 4.24 Temperature changes of salted potato and salted white radish in 0.75salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

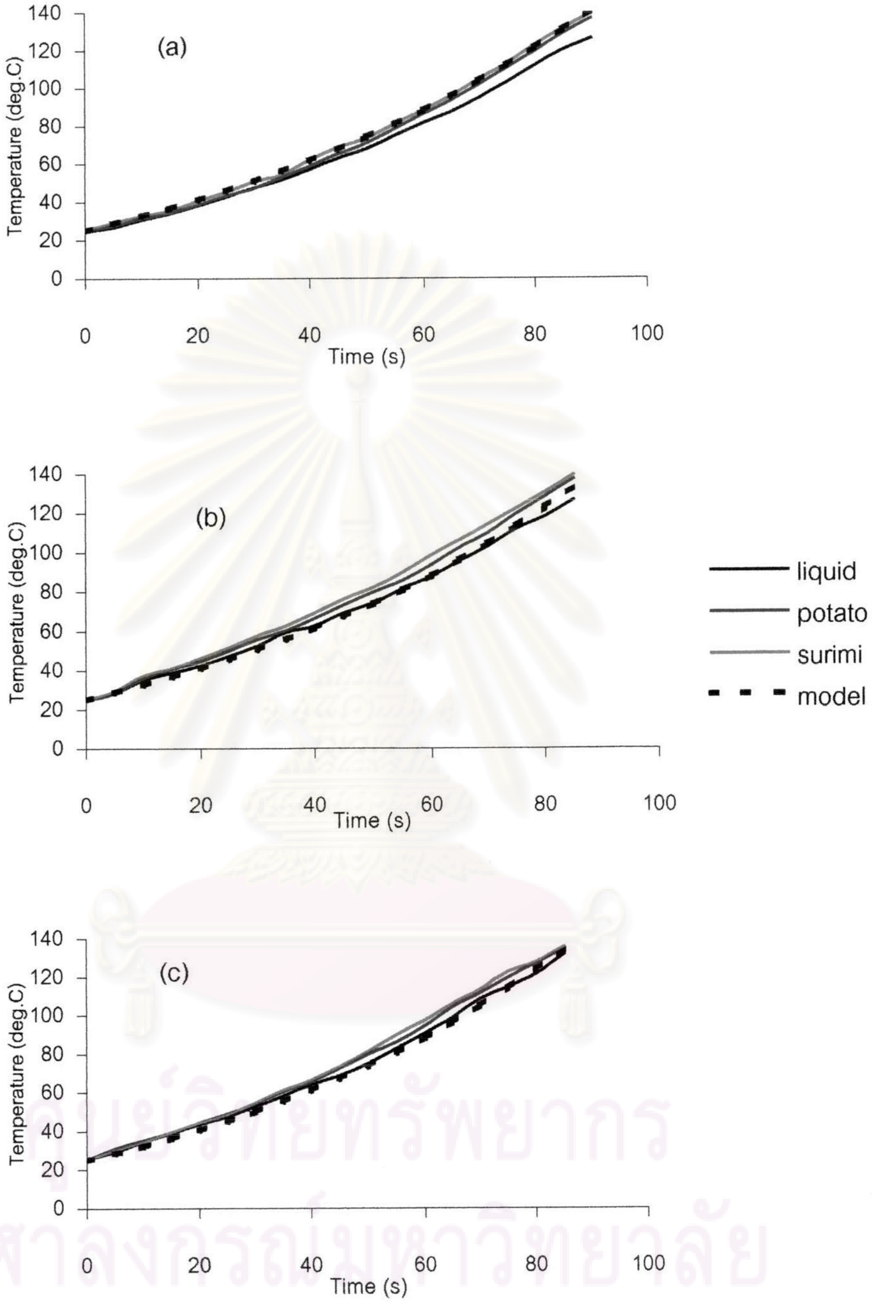

Figure 4.25 Temperature changes of salted potato and surimi in 0.75salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

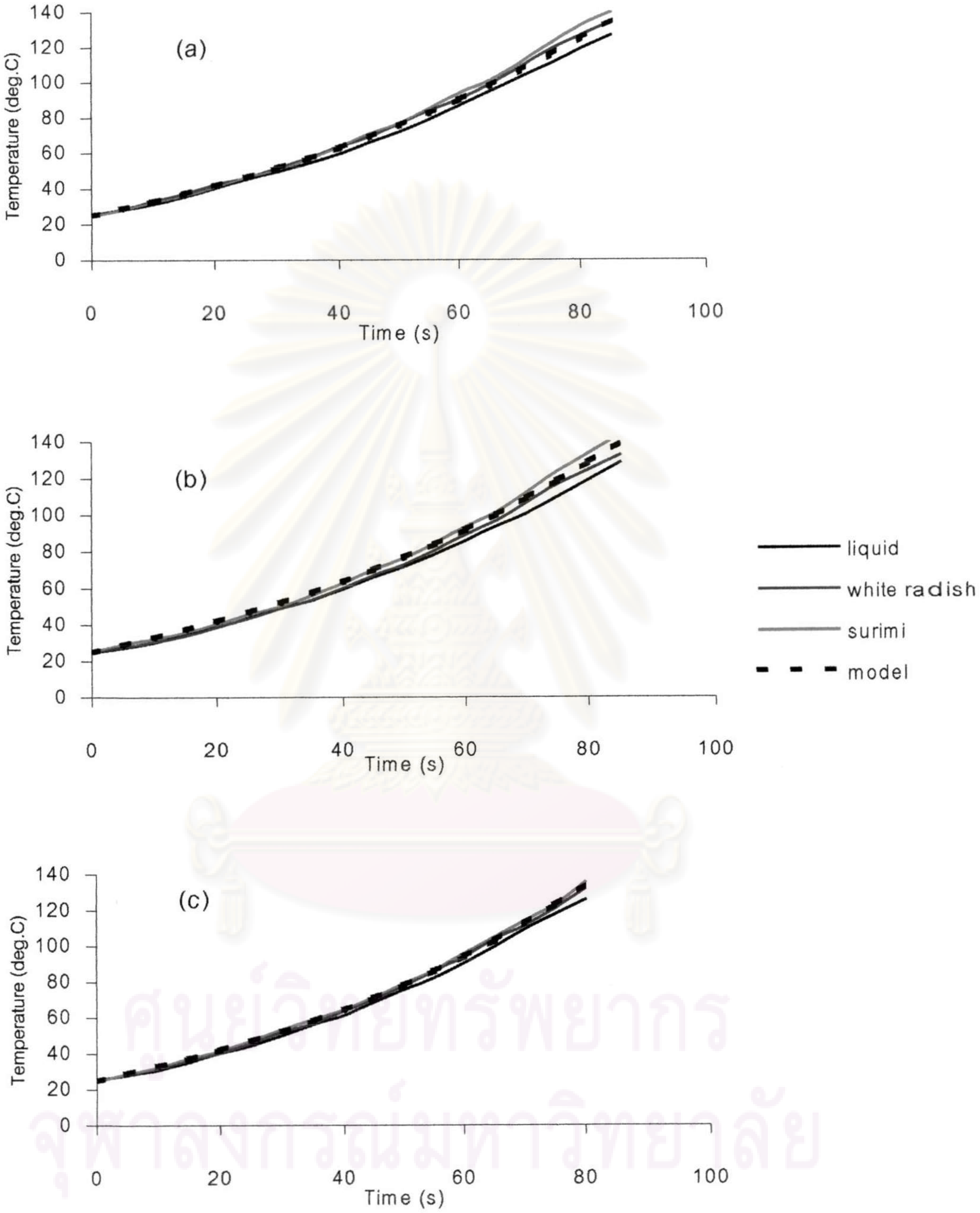

Figure 4.26 Temperature changes of salted white radish and surimi in 0.75salt-2% sugar-4% starch liquid at various volume fractions
(a) = 0.2 vf, (b) = 0.4 vf, (c) = 0.6 vf

4.8 The efficiency of energy conversion from electrical energy to thermal energy

Verification of the efficiency of energy conversion in ohmic heating could be possibly determined from the measured voltage and current as energy input and the thermal energy associated with temperature rise. Figure 4.27 and 4.28 showed the thermal energy compared to the system energy input, for single-type and two-type solids in liquid. The rate of energy input generally matched the thermal energy dissipation fairly close, indicating that energy losses through the walls were small. Thus in ohmic heating, the energy efficiency was considerably high (>90%) in all cases studied in this experiment which agreed with those claimed as advantage of ohmic heating (Parrot, 1992; Sastry and Barach, 2000). However, slight difference among mixtures was obtained even though the same ohmic heating device and identical experimental condition were used This was possibly due to the temperature rise associated with C_p. As C_p depended on temperature differently among materials, differences among mixtures might be obtained.

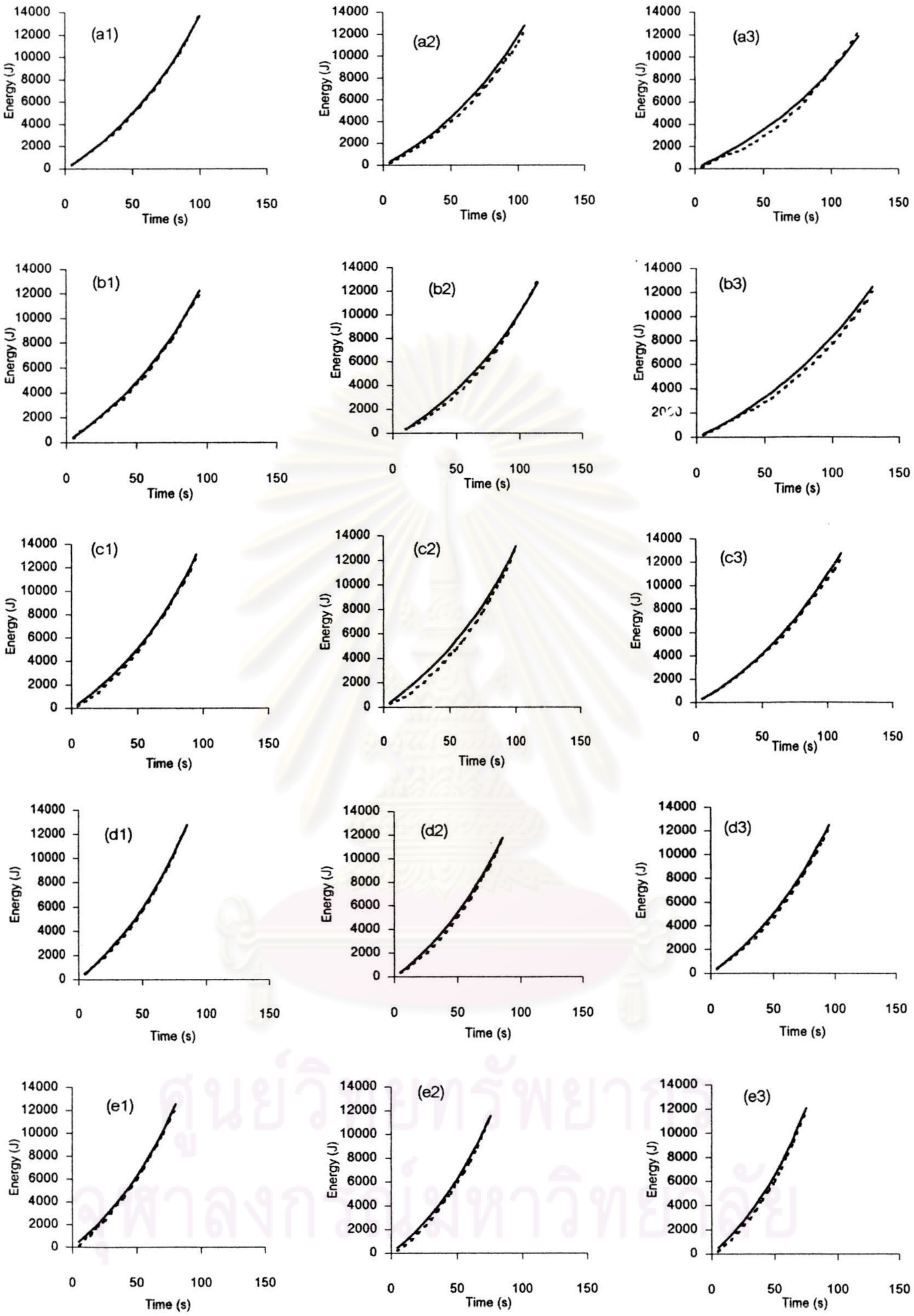

Figure 4.27 Comparisons between the thermal energy from temperature rises to the electrical energy input, for single-type solid in liquid mixtures——— energy input - - - - - - thermal energy

(a) unsalted potato, (b) salted potato, (c) unsalted white radish, (d) salted white radish, (e) surimi

(1,2,3) = 0.2, 0.4, 0.6 vf

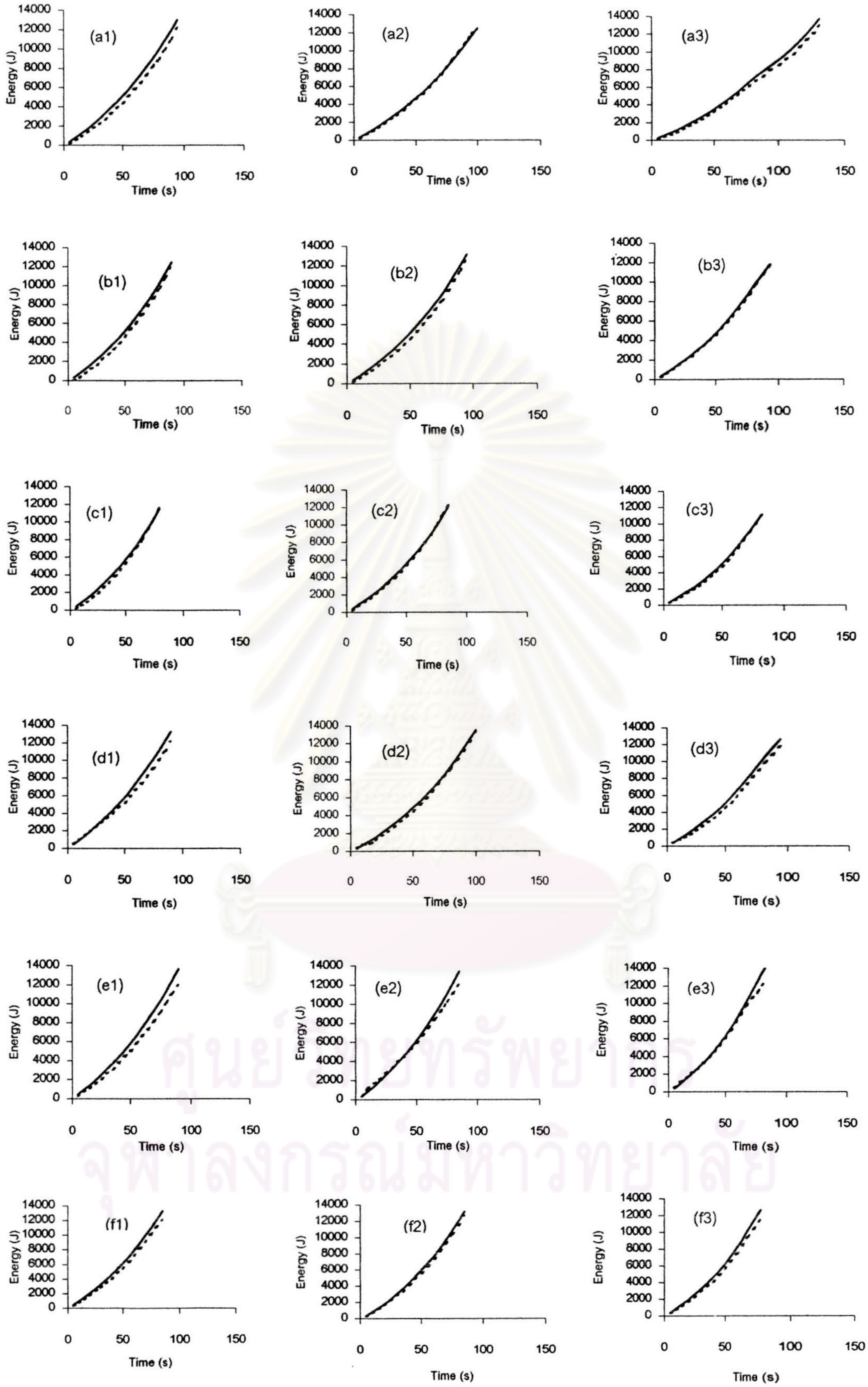

Figure 4.28 Comparisons between the thermal energy from temperature rises to the electrical energy input, for two-type solids in liquid mixtures ——— energy input - - - - - - - thermal energy

(a) unsalted potato and white radish, (b) unsalted potato and surimi, (c) unsalted white radish and surimi, (d) salted potato and white radish, (e) salted potato and surimi, (f) salted white radish and surimi

(1,2,3) = 0.2, 0.4, 0.6 vf