

## CHAPTER V

### Frying Characteristics of Surimi Gels

As described previously, deep-fat frying is a complex process that involves simultaneous heat and mass transfer resulting in counterflow of water vapour and oil at the surface of the piece (Bouchon, 2002). The amount of oil taken up by the food is dependent on various factors including frying temperature and time, moisture content, composition, gel strength, porosity and crust (Saguy and Pinthus, 1995; Gamble et al., 1987; McDonough et al., 1993). Although, it is not clearly understood when and how the oil penetrates into the structure, it has been shown that most of the oil is restricted to the surface region of the fried product (Keller et al., 1986; Lamberg et al., 1990; Farkas et al., 1992; Saguy et al., 1997; Bouchon, 2002). There is also a strong indication that the oil is mostly absorbed during the cooling period (Ufheil and Escher, 1996; Moreira et al., 1997; Bouchon, 2002; Bouchon et al., 2003). For that reason, it is believed that during frying the escape of water vapour would generate an obstacle preventing oil migration into the porous structure, a consequence, oil absorption would be restricted during oil immersion. Oil uptake is essentially a surface-related phenomenon resulting from the competition between drainage and suction into the porous crust once the product is removed from the oil and begins to cool. However, most studies on fried products have been performed in carbohydrate-based products such as potato chips, tortilla crisps, and doughnut. In fact, there are many fried protein-based products such as meat ball and fried chicken which are popularly and widely consumed. The problem is that the protein-based product have complicated compositions. It is difficult to identify the real factors influencing oil absorption. Nevertheless, fish protein gel (surimi gel) is a unique and homogeneous product; it is a good protein model for investigating frying characteristics.

As described in the last chapter, surimi is a heat-induced gel. When it is ground with salt, the solubilization of the proteins results in the formation of a viscous sol. The sol transforms into an elastic and strengthened gel upon heating (Sano et al, 1988 ; Lanier and Lee, 1992). Surimi gel is formed following two heating steps, preheating process below 50°C (setting step) prior to cooking at 90°C. The different temperature in the setting step is important for the conformation of protein and also the resulting structure, and strengths of final gels (Hossain et al, 2001).

The kinetics of water removal, oil uptake, crust formation, temperature profiles and heat transfer inside surimi gel are different from those of fried carbohydrate foods. In this chapter, an attempt to describe gel characteristic during frying, oil absorption, moisture loss and the temperature change inside the gel are presented. Heat transfer during frying is also analysed using unsteady heat conduction equation.

### **5.1 Kinetics of Oil Penetration**

Surimi gels from three setting conditions with three different initial gel strengths of 1,000, 1,700 and 2,300 g.cm were fried at 180 °C for 90, 150 and 180 seconds. Oil absorption in gels was determined in two periods, frying and cooling. The kinetics of oil uptake during frying and cooling are discussed by distinguishing between the two different oil fractions, the surface oil or the oil that remains on the surface and the structural oil which was absorbed during frying or frying and cooling period. The results, which correspond to the arithmetic mean of three different samples, are discussed.

The results for surface oil uptake and absorbed structural oil during frying are shown in Figures 5.1A and 5.1B.

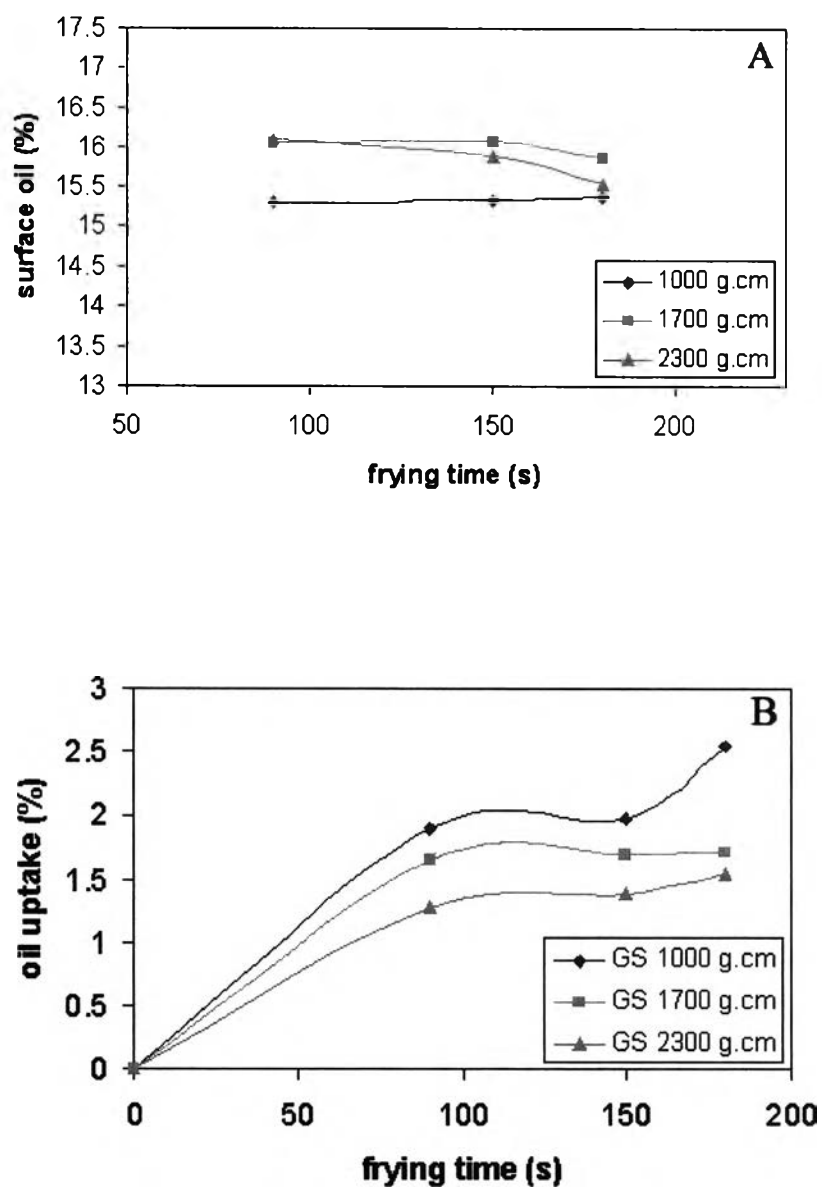


Figure 5.1 Quantities of surface oil (A) and structural oil (B) absorbed by surimi gels during frying.

In the 180 second-fried-sample, the amount of surface oil found immediately after removal of the sample from oil bath was nearly constant at 15% (d.b.) for the 1,000 g.cm surimi gel. But it decreased from 16% to 15.8% and 16.1% to 15.5% during 150 and 180 seconds of frying time for the 1,700 and 2,300 g.cm samples, respectively. However, no significant differences were found between the three investigated times and between the three samples at each investigated time.

Structural oil (Figure 5.1B) represents the oil fraction that is absorbed during the immersion period and gets into the microstructure of surimi gels. Results show that surimi samples absorbed a very small amount of oil while submerging in the oil bath. In all cases the structural oil represented less than 3% (d.b.). Ufheil and Escher (1996) and Bouchon et al. (2003) found similar results in studies of surface oils in potato slices. It is probable that during frying, the higher pressure inside the gel which occurred from vapour development and some amount of vapour escape prohibit oil migration into the porous structure. Hence, the oil absorption is limited during submersion period. However, significant differences were found between the 1,000 and 2,300 g.cm samples at the frying time of 150 and 180 seconds. The results show that higher gel strength samples absorbed lower structural oil. This could probably be because of the more compact structure of higher gel strength sample as shown in chapter 4. With a denser network structure, it could be hypothesized that the obstruction against oil penetration should be greater than the looser one. Thus, the quantity of oil found in the higher strength gel was lower than that of the lower strength gel.

To dig further into the mechanism of oil absorption, the uptake of oil during cooling was investigated and the results obtained were graphically shown in Figures 5.2A and 5.2B.

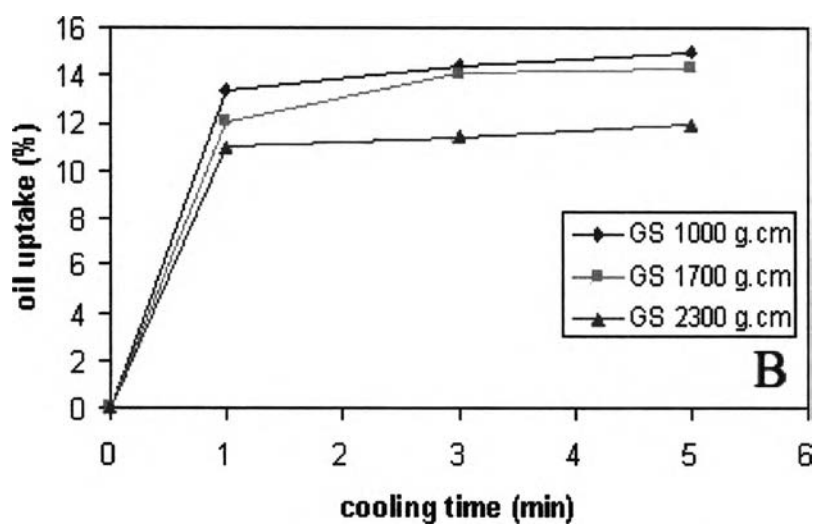
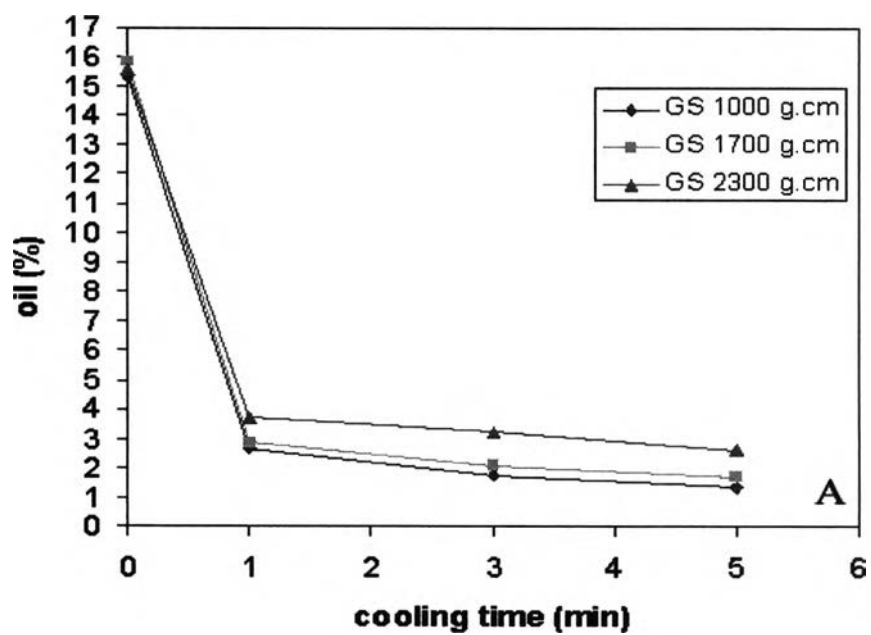


Figure 5.2 Quantities of surface oil (A) and structural oil (B) absorbed by surimi gels during cooling.

It was found that the surface oil rapidly decreased in the first minute of cooling and gradually decreased slightly after 1 minute (Figure 5.2A). In contrary, large amount of oil penetrates at early stage of cooling and more than 80% of total structural oil uptake took place within the first minute of cooling (Figure 5.2B). Figure 5.2A also showed that during the 5 minutes cooling, surface oil decreased from 15.0% to 1.33% for 1,000 g.cm sample, from 15.8% to 1.71% for 1,700 g.cm sample and from 15.5% to 2.59% for 2,300 g.cm sample. During the same cooling period, structural oil uptake rose instantaneously to 12-14% within 1 minute cooling and then, went to plateau values through the rest of the 5 minutes cooling. The structural oil results also showed that oil uptake in the higher gel strength sample was less than that found in the lower gel strength sample. As a result, oil uptake seems to have interrelationship between surface and structural oil. These oil absorption profiles are somewhat similar to those found in fried potato cylinder which fried at 155, 170 and 185 °C for 5 minutes and restructured potato cylinder which fried at 170 °C for 5 minutes. Bouchon (2002) and Bouchon et al. (2003) found that after 10 minutes cooling the amount of oil in fried potato cylinder and restructured potato rose from 0.3-0.6% to 16-20% (d.b.) and from 2% to 22% (d.b.), respectively. Although, the final oil uptake of potato cylinder and restructured potato were 1.5 times higher than the oil uptake in surimi gel, it is obvious that almost of the oil is taken up only at the end of frying when the products are removed from the oil. Ufheil and Escher (1996) reported similar results. They concluded that most of the oil was taken up only at the end of frying.

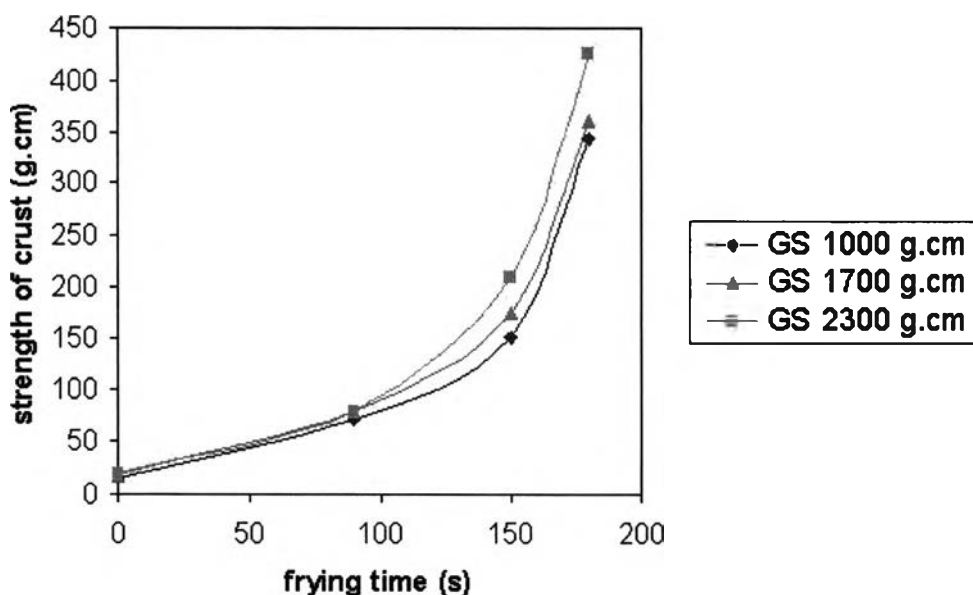
It is credible that the increase of oil penetration during cooling should consequent from the little surface damage that created voids during crust development. Ufheil and Escher (1996) suggested that the oil uptake resulted from the competition between drainage and suction into the porous of the crust once the sample was removed from the oil and began to cool. Additionally, Bouchon et al. (2003) concluded that (1) the largest proportion of the oil, which ended up in the fried potato, was sucked into the porous crust region after the potato was removed from the oil; (2) the balance between oil in the crust and residual structural oil was

the result of the competition between capillary suction into the crust region and drainage along the surface of the product.

Moreover, results in Figure 5.1 and 5.2 show that the different strength of surimi gels have an effect on oil uptake. Increase in gel strength decreases oil uptake. The results are similar to those of fried restructured potato obtained by Pinthus et al. (1992). They concluded that oil uptake was affected markedly by gel strength and oil uptake decreased as gel strength increased.

## **5.2 Kinetics of Crust Development during Frying**

Kinetics of crust development in surimi gel during frying was studied by using texture analyzer to determine the crust strength and scanning electron microscopy (SEM) to analyse its microstructure. Results are shown in Figure 5.3 and 5.4.



**Figure 5.3** Strengths of surimi gel crusts during frying at 180 °C for 180 seconds.

Figure 5.3 shows that crust strengths increased from an initial value of 16-19 g.cm to 343-424 g.cm by increasing of frying time from 0 to 180 seconds at 180 °C. This result can be explained as follows: when frying begins, surface water that evaporates at a very high rate produces rapid dehydration of the outer tissue. This transformation leads to thin crust formation with a porous, dehydrated and permeable surface structure (Bouchon, 2002). When the frying time proceeds, more water evaporates, results in expansion and thicker of the dried crust.

Pedreschi et al. (2001) studied the textural characterization and kinetics of potato strips during frying. They found that the surface of french fry was initially soft ( $t < 6$  min) due to the gelatinization of starch, then hardened. The initial softening was not observed in surimi gel during progressively frying.

Cheftel, Cug and Lorient (1985) stated that the rate of protein denaturation could increase about 600 times when the temperature rose by 10 °C in the range

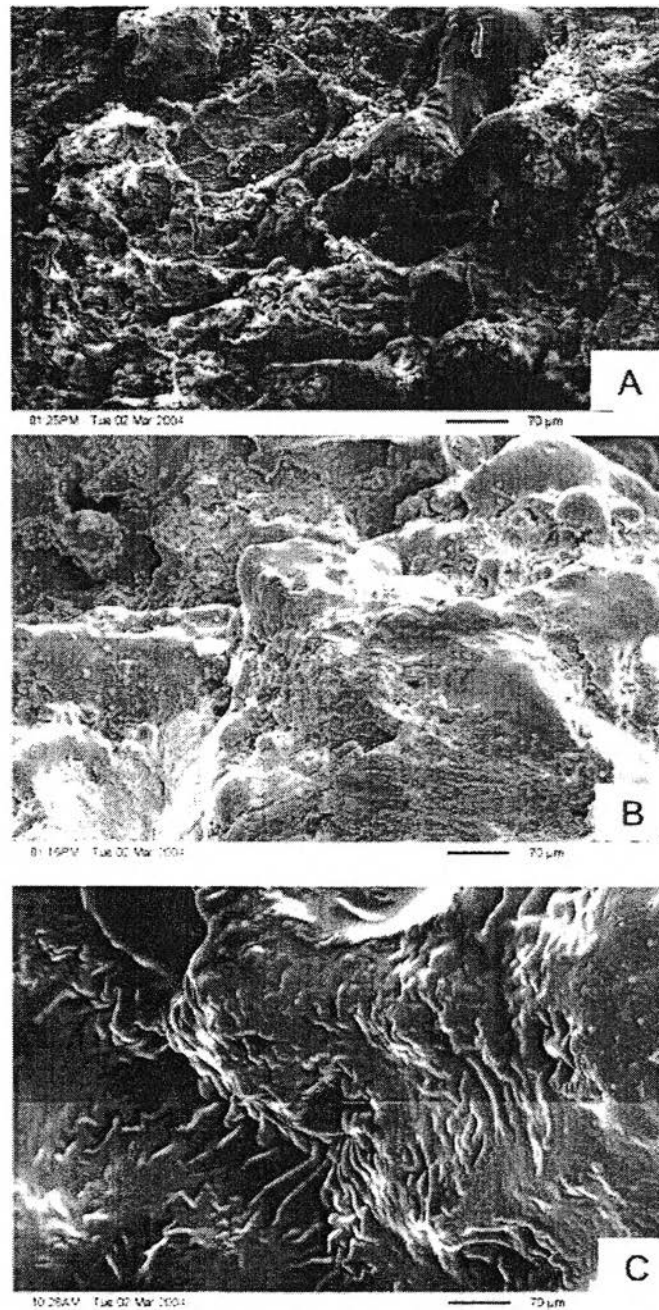


typical of denaturation. This phenomenon may attribute to the sudden formation of a harden crust surface on the fried surimi gel.

The SEM images of the surface area of several gel crisps are shown in Figure 5.4. The variation in roughness of the different fried surfaces is clear. The high initial gel strength sample seems to develop smoother crust surface and the roughness increase with the decrease of gel strength.

The results can be explained as follows: the structure of the high gel strength sample become highly compact as can be seen in the network pictures of surimi gel in chapter 4, therefore the open cells are smaller. Hence, a smooth crust can be formed during surface water evaporation and escape. On the other hand, the rougher crust formes on the low strength sample surface. However, SEM images only allow qualitative observations, hence no quantitative data can be derived from the collected microphotographs.

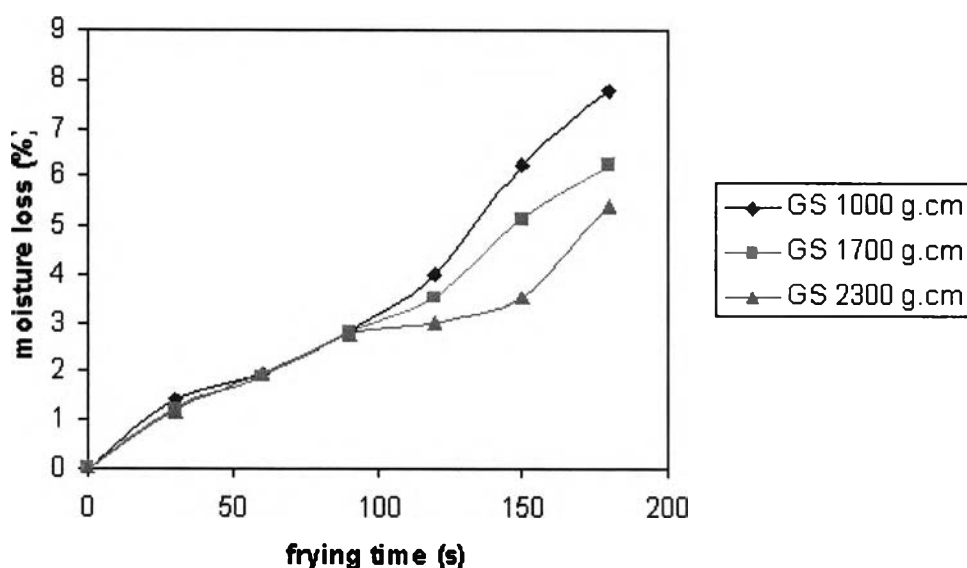
The crust surface of fried surimi gel is much denser and smoother in comparison with fried tortilla crisp. McDonough et al. (1993) studied structural change in corn tortilla crisps using SEM. They found that the surface of tortilla was rough with some large and small diameter holes formed on the surface, as a result of steam venting through the surface during frying. Similarly, fried restructured potato crisps also showed roughness surfaces and sponge-like network structure (Bouchon, 2002). The difference of fried surimi gel and restructured potato surfaces resulted in the different oil absorption as mentioned previously. This might due to the fact that the dense surface and stronger solid structure of surimi gel can withstand a high steam pressure. In addition, a smooth surface not only facilitates oil drainage but is also less susceptible to oil absorption. As a result, a lower oil uptake was observed in fried surimi gel comparing with that found in fried restructured potato product. With this same reason, oil absorption in the higher strength surimi gel was lower than that found in the lower strength one due to its denser and smoother crust.



**Figure 5.4** Scanning electron microphotographs of defatted surfaces of surimi gels at 1,000 g.cm (A) 1,700 g.cm (B) 2,300 g.cm (C) initial gel strengths, after frying at 180°C for 3 minutes. Magnification = 500x.

### 5.3 Water Removal

As previously mention, the dense elastic crust formation outside of the gel has a low permeability effect which results in a heavy restriction of steam escape during frying. Thus, water loss from the 2.5 cm diameter gel in three minutes frying was relatively low (Figure 5.5).

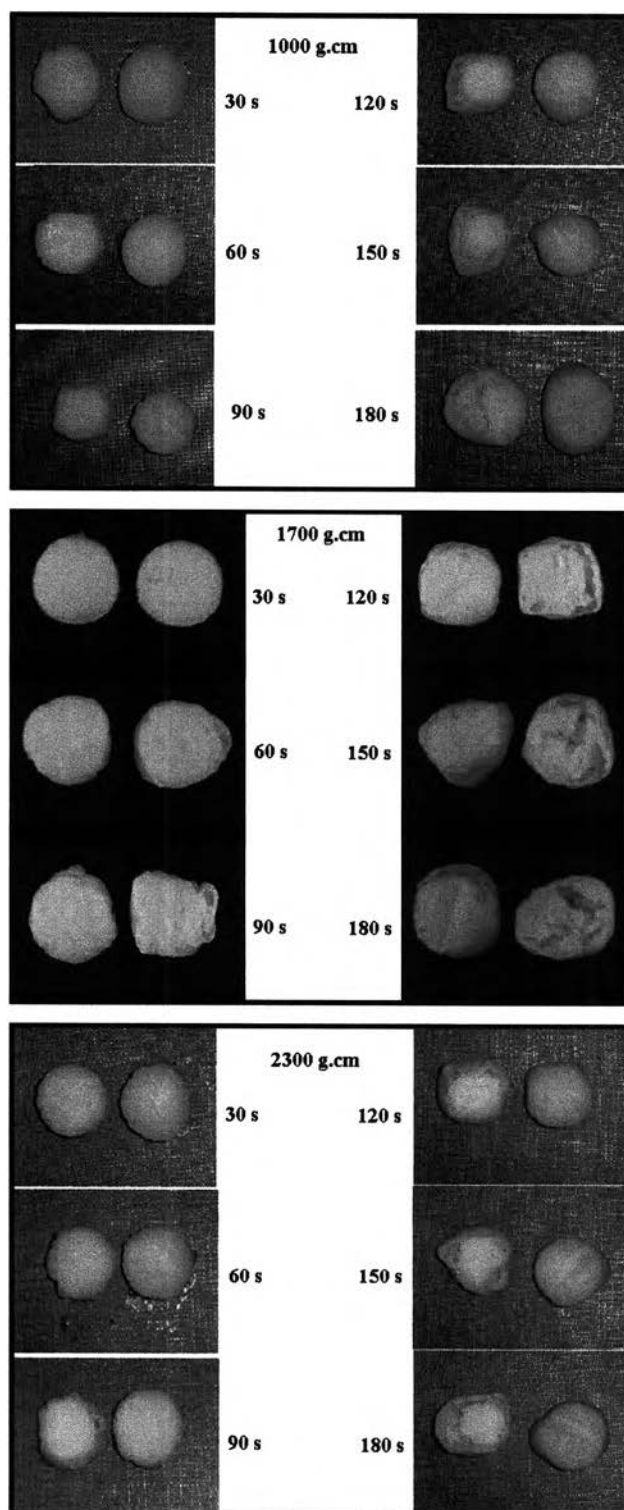


**Figure 5.5** Water loss in surimi gels fried at 180 °C for 180 seconds.

From Figure 5.5, during the first 90 seconds of frying, the rates of water loss from all samples are the same. During this time, only surface water is lost resulting in the formation of dry crust. Once the crust is form, the inner water loss is restricted, resulting in a pressure build-up inside the gel which causes texture disruption and voids development as evident in Figure 5.6. It can be argued that the voids get filled with steam which evaporate and condense within the voids, acting as a heat pipe (Walstra, 2003). Subsequently, when the pressure inside the gel exceeds the threshold limit of crust, vapour escapes through its. The rate of water loss from the gel depended on strengths of the initial gel and crust surface. The rate of water loss from the 1,000 g.cm gel was the highest while that of the 1,700 g.cm sample was

static. For the highest strength sample (2,300 g.cm), the amount of water loss was constant at 3% during 90 to 150 seconds of frying then increased after 150 seconds. These results implicate that both the strength of initial gel and the elastic crust can resist both water escape from the gel and oil penetration into the gel and lead to the limitation of both water loss and oil absorption.

Several researchers have focused on the moisture loss occurring during the frying of carbohydrate-based products such as potato chip, potato crisp and tortilla crisp. Water loss behaviors in products are somewhat different from that found in surimi gel. Bouchon (2002) and Ashkenazi et al. (1984) found that the rates of water loss in potato cylinder and potato strips were high at early stage of frying. Afterwards, they decreased and finally became constant. But for surimi gel, the rate of water loss depended on the strengths of the initial gel and the crust developed during frying. Hence, the difference between water loss characters in fried surimi and fried potato is a consequence of the difference in crust properties as mention earlier. The kinetics of water removal is important to predict the temperature profile inside the structure. Most studies have focused on modeling moisture loss and prediction of temperature distribution inside potato chip or crisp. A key question is whether a similar approach can be adopted for frying surimi gel. The next section demonstrates a crucial difference in temperature distribution inside frying potato chips and surimi gels.



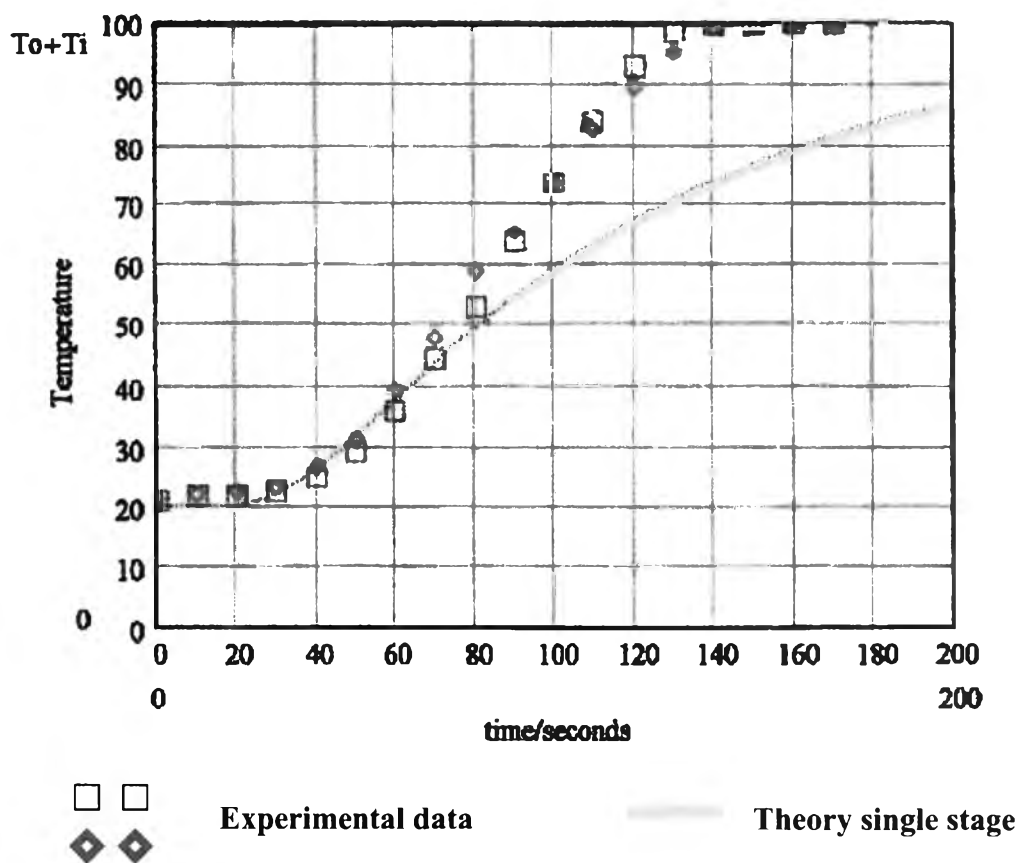
**Figure 5.6** Microphotographs of cross-sectioned surimi gels during frying at 180 °C for 30-180 seconds.

#### 5.4 Heat Transfer in Surimi Gel during Frying

Fish protein gels are made by heat-setting a protein-rich extract from white fish. The myofibrillar proteins are mainly responsible for the elastic gel. To describe the heat transfer in the gel, an approximate first order model of the heat transfer inside the cooking gel following the model of potato chip was developed by assuming that the radius of the gel is constant and equal to the outside radius of the sample. The temperature at the crust/gel interface is taken to be constant at 100°C, the normal boiling point of water.

$$\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right) \quad (5.1)$$

When the above equation is solved using the following initial and boundary conditions, the result follows the yellow line in Figure 5.7. The figure shows that the model can only be fitted with the experimental results for the first 90 seconds. The reason is the formation of the crust. This crust has a lower permeability than the undehydrated gel: the rate of steam escape is heavily restricted during frying. Thus, during surimi frying water loss is considerably lower than in potato frying. Further, the microphotographs of fried surimi (Figure 5.6) show that after around 60 - 90 seconds the internal gel structure breaks down. The voids are filled with steam, acting like a heat pipe resulting in a higher rate of heat transfer after 90 seconds of frying.



**Figure 5.7** Comparison between experimental and one-stage predicted center line temperature for surimi gel frying at 180 °C for 180 seconds.

Hence, to describe the temperature distribution in all process, a simplified two-stage model was developed by assuming that the thermal diffusivity of the gel,  $\alpha_1$ , changes to a new value  $\alpha_2$  at a time  $t_f$ ; corresponding to the time at which the gel structure breaks down. In reality there is probably a transition between the conditions. It is assumed that the gel has an initial temperature  $T_i$  and that the interface temperature is raised instantaneously at the start of frying to 100°C. Neglecting heat transfer through the ends of the gel cylinder, the temperature distribution inside the gel during the first stage of heating is governed by:



$$\frac{\partial T_1}{\partial t} = \alpha_1 \left( \frac{\partial^2 T_1}{\partial r^2} + \frac{1}{r} \frac{\partial T_1}{\partial r} \right) \quad (5.2)$$

with: IC:  $T_1 = T_i$   $\forall r$  at  $t = 0$

BC:  $T_1 = 100^\circ\text{C}$   $r = R, 0 < t < 90 \text{ s}$

During the second stage of heating, the temperature distribution is given by:

$$\frac{\partial T_2}{\partial t} = \alpha_2 \left( \frac{\partial^2 T_2}{\partial r^2} + \frac{1}{r} \frac{\partial T_2}{\partial r} \right) \quad (5.3)$$

with similar boundary conditions ( $\forall t > t_f$ ) and the following initial condition

IC:  $T_2(r, t_f) = T_1(r, t_f)$   $\forall r$  at  $t = t_f$

Following Carslaw & Jaeger (1959) and Crank (1975), the solution for  $T_1$ , the temperature distribution during the first stage of heating, is:



$$T_1(r,t) = Ti + (100 - Ti) \left[ 1 - 2 \sum_{n=1}^{\infty} \frac{\exp(-\alpha_1 a_n^2 t) J_0(ra_n)}{b_n J_1(b_n)} \right] \quad (5.4)$$

where  $J_0$  and  $J_1$  are Bessel functions of the first kind,  $a_n$  are the roots of the equation  $J_0(R, a) = 0$  and  $b_n$  are the roots of  $J_0(b) = 0$ , so that  $b_n = a_n R$ .

The temperature distribution in the second stage of heating, i.e. after  $t_f$ , is then (Carslaw and Jaeger, 1959; Crank, 1975):

$$T_2(r,t) = Ti + (100 - Ti) \left[ 1 - 2 \sum_{n=1}^{\infty} \frac{\exp(-\alpha_2 a_n^2 (t - t_f)) J_0(ra_n)}{b_n J_1(b_n)} \right] + \frac{2}{R^2} \left[ \sum_{n=1}^{\infty} \frac{\exp(-\alpha_2 a_n^2 (t - t_f)) J_0(ra_n)}{(b_n J_1(b_n))^2} \right] \int_0^R r T_1(r, t_f) J_0(ra_n) dr \quad (5.5)$$

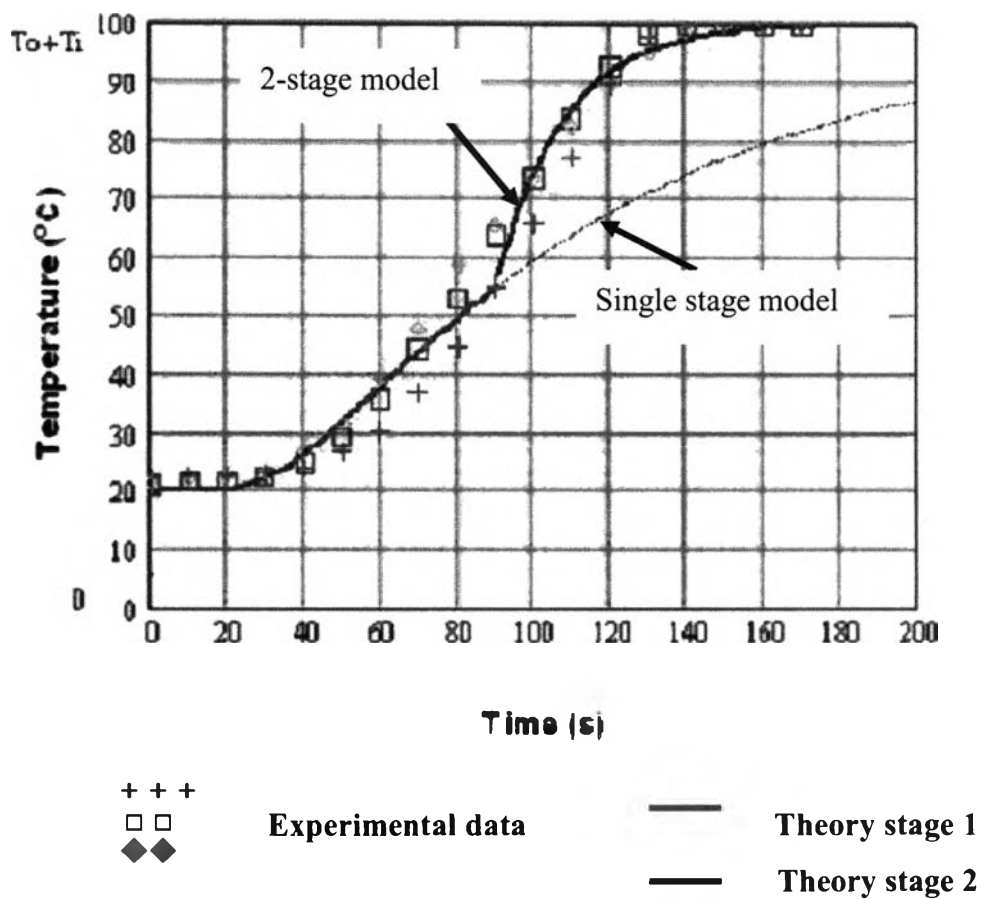
The thermal diffusivity during the first heating stage corresponds to the physical properties of the initial (heat set) gel. An estimate of this value ( $\alpha_1$ ) can be obtained from the temperature profile during heat setting or heating the gel. As the gel is disrupted in the second stage voids appear, and it is argued that these are filled with steam, which will evaporate and condense within the voids, acting rather like a heat pipe (Walstra, 2003). The voids could thus be assumed, for modeling purposes, to have very high thermal conductivity. Maxwell's theory for the conductivity of a two-phase medium containing randomly distributed voids predicts that the effective conductivity of the ensemble,  $k$ , is related to the conductivities of the vapour phase  $k_v$  and the protein phase  $k_b$  by:

$$k = \frac{k_b [k_v + 2k_b - 2\varepsilon(k_b - k_v)]}{[k_v + 2k_b + \varepsilon(k_b - k_v)]} \quad (5.6)$$

where  $\varepsilon$  is the voidage fraction. It can be assumed, as argued above, that  $k_v$  is much higher than  $k_b$ . It is also assumed that the density of the voids is much lower than the density of the protein phase  $\rho_b$ , so that the density of the ensemble  $\rho \sim \rho_b (1 - \varepsilon)$ . Thus, with these assumptions, the thermal diffusivity of the void-filled region,  $\alpha_2$ , is related to the diffusivity of the protein phase,  $\alpha_1$ , by:

$$\alpha_2 = \alpha_1 \frac{(1 + 2\varepsilon)}{(1 - \varepsilon)^2} \quad (5.7)$$

Experiments were carried out to measure the centre-line temperatures during frying versus time at three gel strengths and a frying temperature of 180 °C (Figure 5.8).



**Figure 5.8** Experimental and predicted centre line temperatures during frying of 2.5 cm diameter fish protein gels at 180 °C.

The experimental results are also compared in the figure with the theoretical predictions from Equations 5.4 and 5.5 above. The value of the gel thermal diffusivity  $\alpha_1$  ( $=3.1 \times 10^{-7} \text{ m}^2\text{s}^{-1}$ ) was obtained from conductive heating experiments on the surimi gel. The time  $t_f$  marking the transition from the first to the second stages of heating, i.e. the disruption of the gel, was taken to be 90 seconds, corresponding approximately to the photographic evidence.

The thermal diffusivity in the second stage,  $\alpha_2$ , was estimated from the extension of Maxwell's theory (Equation 5.7) using a voidage fraction of 0.4. This value corresponds to an average voidage fraction of the gels. Maxwell's theory predicts that  $\alpha_2$  equal 5 times of  $\alpha_1$  i.e.  $1.53 \times 10^{-6} \text{ m}^2\text{s}^{-1}$  and this value has been used in the comparison in Figure 5.8. It is impossible to obtain a good fit between the experimental data and a model with constant thermal diffusivity, as illustrated by the dotted line which is a continuation of the first stage model. The temperature profile during the second stage of heating was obtained by numerical integration of Equation 5.5 using the value of the temperature profile at  $t = 90$  seconds as initial condition. It is seen that the approximate theory outlined here gives a very reasonable fit to the experimental results, suggesting that the theory correctly captures the basic mechanism of heating for surimi gels.

## 5.5 Conclusion

The oil absorption into surimi gel mostly occurs during cooling period rather than the frying period. However, the amount of oil penetration into the gel and the amount of water loss from the gel are limited by the formation of elastic crust on the surface of the gel. The heat pipe-like-heat transfer is evident. A mathematical heat conduction model of infinite cylinder system with step change of thermal conductivity was developed to predict the temperature distribution in surimi gel. The model was able to predict temperature distribution inside the gel during frying at  $180 \text{ }^\circ\text{C}$  for 3 minutes and gave a good agreement with the experimental data.