Modelling the Kinetics of Water Loss during Deep-Fat Frying of Potato Particulates

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Abstracts

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We developed an empirical model to describe the water loss during deep-fat frying. Raw potato particulates were sliced to form cylinders and subjected to the deep-fat frying at isothermal temperatures of 160, 190, and 220°C. The microstructure properties were assessed by Field Emission Scanning Electron Microscope (FESEM). The plot of the water content versus the frying time showed two distinct regions. A first-order kinetic model correlated with the two irreversible serial rate processes, rapid process and slow process, was hypothesised to describe the water loss during frying. The results showed the simultaneous two first-order kinetic models adequately predicted the water loss of potato particulates during isothermal frying. The effect of temperature on the rate constants, k_1 and k_2, for the two processes was adequately modelled by the Arrhenius relationship. The observations of structural changes on the surface and in the inner section of potato particulates are critical. These physical pieces of evidence support our assumption that the mechanisms of the water loss (two-stage rate processes) before and after the transition time are different.

Keywords: Arrhenius relationship; activation energy; structural changes; FESEM

Deep-fat frying is widely used in food processing, which consists basically of immersion of food pieces in hot vegetable oil. Frying is often selected as a method for creating unique flavours and texture in the processed foods that improve their overall palatability (Moyano & Pedreschi 2006). Their desirable flavour, colour, and crispy taste make them very popular with the consumers.

Deep-fat frying is a process of simultaneous heat and mass transfer. Two mass transfers take place in opposite directions within the material. Heat is transferred from the oil to the food, which results in the evaporation of water from the food while oil is absorbed in it. With starchy products, water and some soluble materials escape from the products and oil enters in the food (Blumenthal 1991). Sometimes, even fat can escape from the product in the oil bath during the frying of raw material presenting a significant fat content such as meat or fish (Oroszvari *et al.* 2005).

During deep-fat frying, starch gelatinisation and swelling occur very rapidly, thus making the potato cells with a dense starchy interior capable of supporting dehydration with shrinkage (Ziaiifar *et al.* 2008). Many researchers used potato strips or potato slices as fried samples and commercial electric fryers as heating sources to study the kinetics of the water loss and oil uptake during deep-fat frying (Moyano *et al.* 2002; Pedreschi *et al.* 2008; Debnath *et al.* 2009). Moyano *et al.* (2007) developed a kinetic model based on two irreversible serial chemical reactions to fit experimental data of texture changes during thermal processing of potato products.

In establishing a kinetic model to describe the mass transfer phenomena during the frying process, the most important principle is the constant oil temperature during deep-fat frying (Krokida *et al.* 2000). However, the potato samples were cut into different sizes or shapes, thus affecting the heat and mass transfer and the rising rate of the temperature up to the frying temperature in the middle of the sample. The sample size and the effect of the temperature control on the heating installation would influence the constant of oil temperature, even involve the correct kinetic parameters. In addition, the procedure of drying potatoes after frying is also pivot. When the fried samples were removed from the fryer, their temperature was still much higher than 100°C; so heat and mass transfer still proceeded in the fried samples. But most of the fried samples were left at the room temperature until the sample temperature dropped to the room temperature. However, in order to obtain useful and meaningful information on the contribution of frying kinetics, isothermal temperature should be accomplished and frying procedures must be designed carefully.

The concept of the fractional conversion method has extensively been applied in chemical engineering (Levenspiel *et al.* 1972; Hill 1997). A simple first order reaction, A → B is assumed in the method. An though it is used to describe the reaction kinetics from the molecular standpoint, it has also been employed widely in the food research area because the major reactions occurring in foods also follow the well-established first order reaction kinetics. Thermal destruction of microorganisms, most of the nutrients, enzyme and quality factors (moisture, texture, flavour, colour) are followed basically by the first order kinetics (Welt *et al.* 1993, 1994; Bourne 1995; Rizvi & Tong 1997; Ryan-Stoneham & Tong 2000; Fu *et al.* 2003a,b,c,d, 2005; Fu 2007).

Equation (1) is used in food research studies and it taken as granted for an irreversible first order reaction at a constant temperature. This may be wrong if the reactant concentration is not zero when the reaction is very long (Fu 2007).

$$\ln C_t/C_0 = -kt \quad (1)$$

The fractional conversion (*f*) of a reaction is defined as the following:

$$f = (C_0 - C_t)/(C_0 - C_{\mathrm{inf}}) \quad (2)$$

where: k – rate constant with a unit of 1/time; t – heating time; C_0 – initial concentration; C_t – concentration at time t; C_{inf} – concentration when the reaction is completed

If C_{inf} approaches zero when the reaction is completed, Eq. (2) can be reduced to the following:

$$f = (C_0 - C_t)/(C_0) \quad (3)$$

$$1 - f = C_t/C_0 \quad (4)$$

$$\ln C_t/C_0 = \ln(1 - f) = -kt \quad (5)$$

When quality factors such as texture, flavour, colour, and moisture have been lost during the process at a constant temperature at a prolonged time, C_{inf} need not be zero, so the value of C_{inf} should be applied and Eq. (5), not Eq. (1), should be used for determining the kinetics (Fu 2006, 2007).

Lisinska and Golubowska (2005), investigating the structural changes of potato tissue during French fries preparation, concluded that the greatest changes in the potato tissue resulted from thermal processes and in the ultimate texture of French fries which was developed by the penetraton of fat into the external layer of strips during frying. Bouchon and Aguilera (2001) investigated the use of several different microscopical methods as well as image analysis techniques to study the frying on the microstructural level. Their results indicated that frying induces major structural changes on the surface of foods influencing the oil uptake while not causing major damage to the inner cell structure of potato pieces except for shrinkage and dehydration (Bouchon & Aguilera 2001). Moreira *et al.* (1997) studied the factors affecting the oil uptake in tortilla chips in deep-fat frying. Scanning electron micrographs showed that during frying the pore size distribution developed was the main cause for oil absorption during cooling. Small pores trapped more air during frying, which resulted in a high capillary pressure during cooling and then in a higher final oil content (Moreira *et a*l. 1997).

Several researchers tried different approaches to investigate the changes of texture, crust colour, and micronutrients during deep-fat frying (Bourne 1995; Bouchon & Aguilera 2001; Moyano *et al.* 2002, 2007; Debnath *et al.* 2003; Kumar *et al.* 2006; Avallone *et al.* 2009) but not too many published studies have shown the water loss during the frying process especially emphasised in isothermal condition. The objectives of this work were to fulfil isothermal heating condition and measure water loss in the cylindrical potatoes particulates during deep-fat frying at 160, 190, and 220°C. A simultaneous first-order kinetic model correlated with the two irreversible serial rate processes was hypothesised and evaluated. The microstructure properties were assessed using Field Emission Scanning Electron Microscope (FE-SEM).

MATERIAL AND METHODS

Materials. Potatoes (79% moisture content) were procured from a local market and stored in a dark room at 4°C. Soybean oil (Uni-President, Tainan, Taiwan) was used as the frying oil. Fleshy cylindrical potatoes (0.006 m diameter × 0.006 m length) were obtained with a circular cutting mould (cork borer) from the parenchymatous region of potato tubers. Prior to frying, the potato cydinders were rinsed immediately after cutting with distilled water to eliminate some starch material adhering to the surface prior to frying and stored in a humid container with moistened towels to prevent excessive surface drying before frying.

Frying conditions. The isothermal heating installation consisted of a temperature controller with a temperature sensor (TC-400P; Renson, Taichung, Taiwan), heating tape (B00101-020, size 1×2 ft; Brisk Heat®, Ohio, USA), heating plate with a stirres (HSM-102; Fargo, Taipei, Taiwan), and a beaker (600 ml; Pyrex®, Massachusetts, USA). The frying temperatures were constantly controlled by the temperature controller with a temperature sensor. Potato-to-oil ratio was kept at 1 : 1200 (g/ml) to maintain the frying temperature constant. The oil was pre-heated for 30 min prior to frying, and discarded after 6 h of use.

A Luxtron Fluoroptic Thermometry System (Luxtron Model 755; Luxtron Corp., Mountainview, USA) was used to measure the sample temperature. The temperature range of the probe was up to 350°C with an accuracy of ± 1°C. The optical fiber temperature probe was centred in the potato particulate sample. The diameter of the probe tip was 1 mm which is the thinnest size we could have to measure the temperature with the fastest temperature reading response. The come-up time required for the coldest point in the geometrical centre of the food matrices when heat is first applied was relatively short compared with the total heating time in this study, which is consistent with the definition of isothermal.

An off-line technique was used for measuring the water content. The term off-line water content measurement is used to describe the method in which the residual water content in the sample is measured after the sample has been removed from the deep-fat oil and subsequently subjected to a chill with liquid nitrogen in order to stop the further heat and mass transfer as soon as possible. Fleshy cylindrical potatoes were weighed and then fried in hot oil at isothermal temperatures of 160, 190, and 220°C controlled by the isothermal heating installation. The cylindrical potatoes were fried for 10, 15, 20, 30, 40, 50, 60, 75, 90, 105, 120, 135, 150, 180, 210, and 240 s to determine the amount of water content and oil uptake in the cylinders as a function of time. Fried cylindrical potatoes were weighed and then dried by freeze-drying.

Analytical methods. The oil content was determined by Soxhlet extraction. The dried fried cylindrical potatoes were ground and extracted with ether at 65°C for 5 hours. The oil content was expressed on a dry basis as g of oil/g dry solids. The initial moisture content was estimated by drying the sample at 105°C for 24 h (Debnath *et al.* 2003). The water contents of fried cylindrical potatoes were calculated by subtracting oil and solid contents from the weight of dried cylindrical potatoes. All experiments were run in at least triplicate and the presented results are the average of the values obtained.

Kinetic data analysis. Frying may be seen as a high temperature drying process in a liquid fat medium (Costa & Oliveira 1999). Eq. (6) is used in this study:

$$\ln C_t/C_0 = \ln [(C_t - C_{\mathrm{inf}})/(C_0 - C_{\mathrm{inf}})] = -kt \qquad (6)$$

where: C_t (g/g solid) – water content of the potato particulate samples after a time period, of deep-fat frying; C_{inf} (g/g solid) – equilibrium water content after prolonged deep-fat frying; C_0 (g/g solid) – water content at a specific time, 0; k (1/s) – rate constant of water content

For a first order reaction, the plot of the logarithm of the $[(C_t - C_{\mathrm{inf}})/(C_0 - C_{\mathrm{inf}})]$ vs. time would yield a straight line. The rate constant, k, can be determined from the slope of the regression line (Levenspiel 1972). In this study, water losses obeyed the first order reaction while deep-fat frying is hypothesised. The temperature dependence of the rate constant normally follows the Arrhenius equation:

$$k = A \exp(-E_a/RT) \qquad (7)$$

where: A – pre-exponential factor (units of k); E_a – activation energy (J/mol); R – universal gas constant (8.3136 J/mol·K); T – temperature (Kelvin)

The activation energy and the pre-exponential constant can be obtained through linear regression when the logarithm of the rate constant is plotted vs. the inverse of temperature.

Microstructure properties. The microscope used is a field emission scanning electron microscope (FE-SEM) incorporating a cold cathode field emission gun. Voltage range is from 0.5 kV to 30 kV. The resolution is 1 nm at 15 kV. The attachments of this SEM are: (1) electron dispersion X-ray analysis system (EDX) for chemical analysis and (2) back scattering detector for Z-imaging.

The surface and cross section structures of fried potato particulates were fractured and mounted on aluminium stubs using double adhesive tape. The samples were sputter-coated with platinum (BALTEC, SCD 005) and then viewed in a Field Emission Scanning Electron Microscope (JSM-6700F; JEOL, Tokyo, Japan) at 25–100× magnifications.

Statistic analysis. The apparent yield of the data was analysed using SAS analysis system followed by means separation using Duncan's multiple range test.

RESULTS AND DISCUSSION

Isothermal condition. Process engineers rely on kinetic models to design, optimise and predict the processing. The unsteady-state approach is not desired due to its complexity and use of rigorous mathematical/numerical techniques. The steady-state approach is simple but it requires an isothermal system and uniform temperature profile of the system. Ideally, the sample is instantaneously and uniformly heated to the desired temperature. It is ideal to reduce the come-up time to zero; otherwise it is impossible to achieve this perfect condition (Fu 2004).

The coldest point occurs in the geometrical centre of the cylindrical potato particulate sample. In order to minimise the come-up time, the centre temperature in the cylinder of different diameters and lengths (0.005, 0.006, 0.007, 0.011 m) was monitored. We found the cylindrical sample of 0.006 m diameter × 0.006 m length not to be too small to be handled and it also had a short come-up time for reaching the desired isothermal temperature. Figure 1 shows the centre temperature of the sample (0.006 m diameter × 0.006 m length) during isothermal deep-fat frying at 160, 190, and 220°C. The centre temperature was reached and maintained at a desired isothermal frying temperature in about 10–13 seconds. Compared to the whole period of the frying time of 250 s, the come-up time of 10–13 s is relatively short.

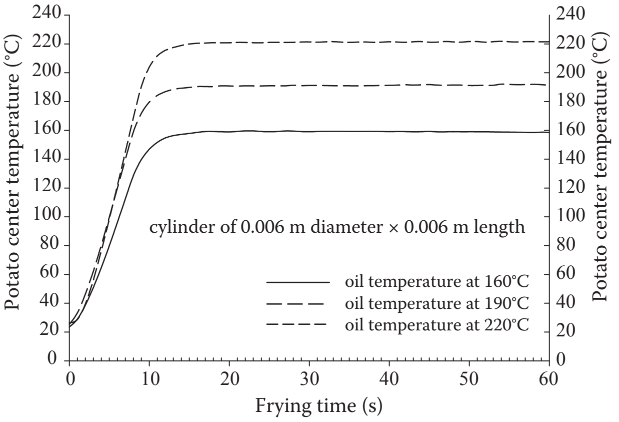

Figure 1. Time–temperature relationship of a potato particulate sample during isothermal deep-fat frying at various temperatures (160, 190, and 220°C)

Modelling of two first-order kinetic rate processes. Reeve and Neel (1960) noted that after 2 min of frying at 140 and 180°C the water content of the fries was approximately the same, even though they claimed that the cellular structures of the samples

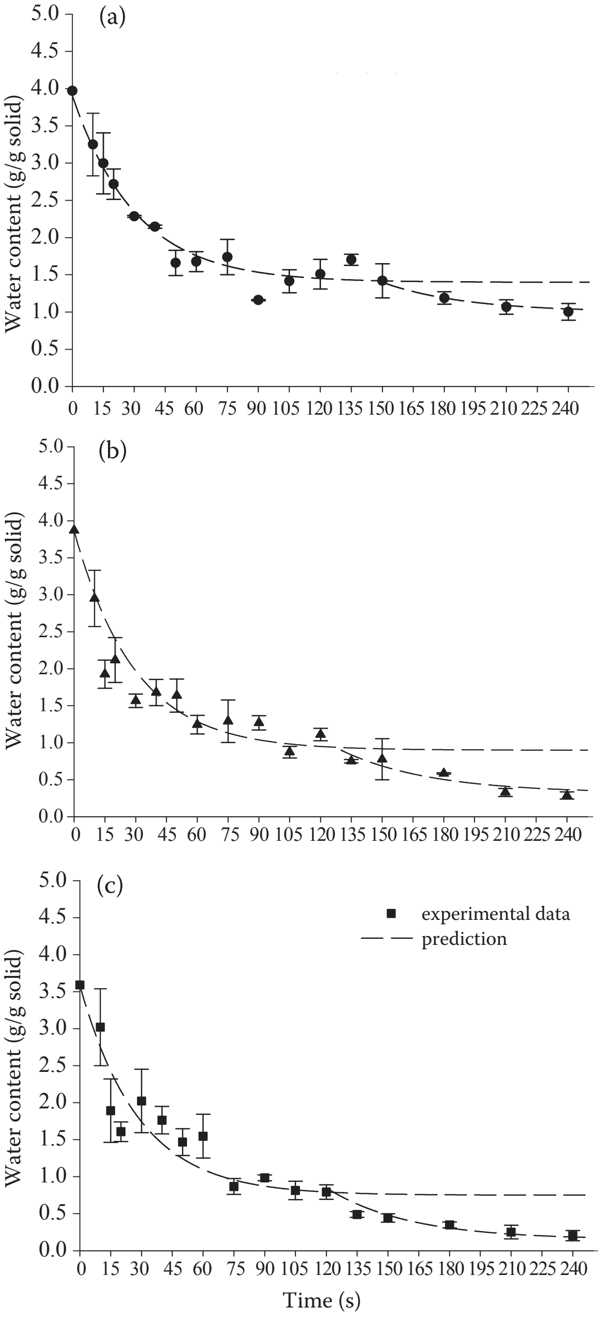

Figure 2. Water content–time curves for potato particulate during isothermal deep-fat frying at various temperatures (a) 160°C, (b) 190°C, and; (c) 220°C

were quite different. This however, did not happen with our samples. With a better temperature control to accomplish isothermal condition, during 160, 190, and 220°C of frying, the average water content of the potato particulates in the samples was not the same (Figure 2) when compared at the same frying time. To be able to get correct data, careful handling of the samples, prevention of the turbulent flow of oil breaking the cell wall, and a good control of the frying temperature are necessary. If one of these factors went wrong, the data would be unreliable.

The plot of the water content versus frying time at isothermal frying temperature in Figure 2 showed two distinct regions. First, there was a rapid loss of water from the beginning up to about 120 to 150 s followed by a slow rate of change for the rest of the frying time. Although there are virtually many equations to fit the experimental data, an ideal mathematical model should be as simple as possible. The linear relationship of the experimental data, the logarithm of the $[(C_t - C_{\text{inf}})/(C_0 - C_{\text{inf}})]$ vs. time (not shown here), suggests that the water content can be fitted by a first order kinetic model. Therefore the following mathematical model was proposed. The region of the rapid process (Eq. 8a) is a rectilinear plot with a steep negative slope. The slow process (Eq. 8b) is also a rectilinear plot with a shallow negative slope. By using the right C_{inf}, if the logarithm of the $[(C_t - C_{\text{inf}})/(C_0 - C_{\text{inf}})]$ is plotted versus time, a linear relationship is obtained. The two rate constants, k_1 and k_2, can then be determined from the slope of the regression line.

Rapid process:

$$\ln C_{t1}/C_0 = \ln [(C_{t1} - C_{\text{inf1}})/(C_0 - C_{\text{inf1}})] = -k_1 t \quad (8a)$$

Slow process:

$$\ln C_{t2}/C_0 = \ln [(C_{t2} - C_{\text{inf2}})/(C_0 - C_{\text{inf2}})] = -k_2 t \quad (8b)$$

where: C_{t1} – water content of the time in the rapid process; C_{t2} – water content of the time after transition time in the slow process; C_{inf1} – equilibrium water content of the rapid process; C_{inf2} – equilibrium water content of the slow process; k_1, k_2 – rate constants of the rapid and slow processes, respectively

Table 1 shows the two first-order rate constants, k_1 and k_2, and transition times for both r the apid process and the slow process. Rsqr of the rate constants for both processes are all larger above 0.982 (figures not shown), the high values for Rsqr supporting the postulate of two first-order rate processes. The value of the rate constant in the region of the rapid process, k_1, is greater than the rate constant, k_2, in the region of the slow process. Table 2 give an example of frying at 160°C where the rate constant (0.032 1/s) of the water loss was small in the first 150 s with 64.7% water being lost in this section. When passing the transition time, the rate constant was changed and the value of the rate constant became even lower (0.020 1/s) and, at the end, 22.7% water was left in the final fried matrix. The reason for the rate constant change in the transition time was due to the structural changes. Reeve and Neel (1960) observed micro-structural changes of the potato samples during frying. They noted that after 2 min of frying at 140 and 180°C the cellular structures of the samples were quite different.

To predict the loss of water, empirical Eqs (9a) and (9b) can be developed using the kinetic data from Table 1.

$$t < \text{transition time: } C_{\text{t}} = C_{\text{inf1}} + (C_0 - C_{\text{inf1}}) \exp(-k_1 t) \quad (9a)$$
$$t > \text{transition time: } C_{\text{t}} = C_{\text{inf2}} + (C_0 - C_{\text{inf2}}) \exp(-k_2 t) \quad (9b)$$

From Figure 2, the prediction based on the model fits quite well the experimental data. The activation energy of the rapid process and slow process could also be calculated by Eqs (10a) and (10b).

$$\ln k_1 = \ln A_1 - (E_{\text{a1}}/R)\ (1/T) \quad (10a)$$
$$\ln k_2 = \ln A_2 - (E_{\text{a2}}/R)\ (1/T) \quad (10b)$$

where: k_1, k_2 – rate constant of the rapid process and the slow process, respectively; E_{a1}, E_{a2} – activation energy of these two processes

The temperature dependence of the rate constant is shown in Figure 3 for these samples in the plot of the logarithm of the rate constant against $1/T$. A straight line with the negative of the slope equals to E_{a}/R. Because of the linearity of the plots, the effect of temperature on the rate constants, k_1 and k_2, for both processes was adequately modelled by the Arrhenius relationship. The average activation

Table 1. The rate constant and transition time for potato particulate samples during isothermal deep-fat frying at various temperatures (160, 190, 220°C)

Temperature (°C)	Transition time (s)	Rate constant (1/s)	
		k_1^* (rapid process)	k_2^* (slow process)
160	150	0.032 ± 0.002	0.020 ± 0.005
190	135	0.034 ± 0.001	0.023 ± 0.006
220	120	0.036 ± 0.002	0.026 ± 0.004

*data reported as mean ± SD

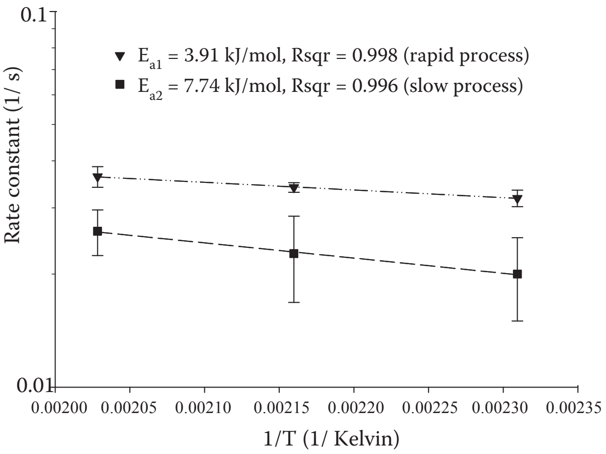

Figure 3. Arrhenius plot for water loss for potato particulate as a function of isothermal deep-fat frying temperatures (160, 190, and 220°C)

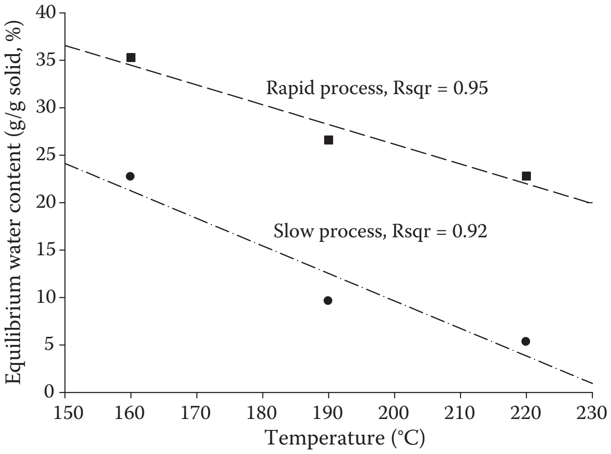

Figure 4. The equilibrium water content (C_{inf}) of potato particulate as a function of isothermal deep-fat frying at various temperatures (160, 190, and 220°C)

energy of the rate constants, k_1 and k_2, was 3.91 and 7.74 KJ/mol, respectively, at the frying temperature from 160°C to 220°C.

The activation energy is the energy barrier that the reactants must overcome in order to react. Therefore the activation energy is viewed as an energetic threshold for a fruitful reaction. The different values of the activation energy for these two processes, E_{a1} and E_{a2}, points to different mechanisms of water loss in the two processes during frying. It is believed that in the slow process the structural changes cause difficulty in the course of the water loss due to the high activation energy needed to complete the process as compared with the rapid process.

The higher is the frying temperature, the smaller is the equilibrium water content, giving values ranging from 1.4 g/g to 0.82 g/g solid in the rapid process (Table 2). During the slow process, the tendency of the water loss is the same as with the rapid process but the values of the equilibrium water content are smaller, ranging from 0.90 to 0.19 g/g solid. It is interesting that both equilibrium water contents, C_{inf1} and C_{inf2}, are functions of the frying temperature with good linearity. With Rsqr 0.95 and 0.92, respectively (Figure 4). In Table 2, the difference between C_{inf1} and C_{inf2} (ΔC_{inf}) is insignificant ($P < 0.05$). This means that irrespective of the frying temperature used, the difference between the equilibrium water contents (ΔC_{inf}) in the two processes is not the function of the frying temperature. The transition time is the time needed to switch from the rapid process to the slow process. Figure 5 shows that the dependence of the transition time on the frying temperature used in the study is perfectly linear, i.e. a higher frying temperature concludes in short transition time needed to transit from rapid process to slow process.

During potato particulate water vapour escapes at frying, at the very beginning, from the potato and the crust becomes thicker as the frying proceeds. Costa *et al.* (2001) observed that the shrinkage rate and thickness of crust increased with the increasing frying temperature. We believe that the crust formation starts at the very beginning and the crust thickness increases with temperature. The higher is the frying temperature, the thicker crust is formed. Because of the large amount of stress caused by the build-up of pressure in the intercellular spaces owing to the water-vapour accumulation, and with no convective/

Table 2. The equilibrium water content and transition time for potato particulate samples during isothermal deep-fat frying at various temperatures (160, 190, 220°C)

Temperature (°C)	Transition time (s)	Equilibrium water content (g/g solid)				
		C_{inf1}*	C_{inf1}/C_0 (%)	C_{inf2}*	C_{inf2}/C_0 (%)	ΔC_{inf}*
160	150	1.40 ± 0.15^{a}	35.3	0.90 ± 0.10^{bc}	22.7	0.50 ± 0.13^{A}
190	135	1.03 ± 0.16^{b}	26.6	0.37 ± 0.06^{d}	9.6	0.67 ± 0.20^{A}
220	120	0.82 ± 0.12^{c}	22.8	0.19 ± 0.04^{e}	5.3	0.62 ± 0.09^{A}

*data reported as mean ± SD; $^{a–e,A}$within a group (C_{inf} and ΔC_{inf}) with different letters are significantly different ($P < 0.05$)

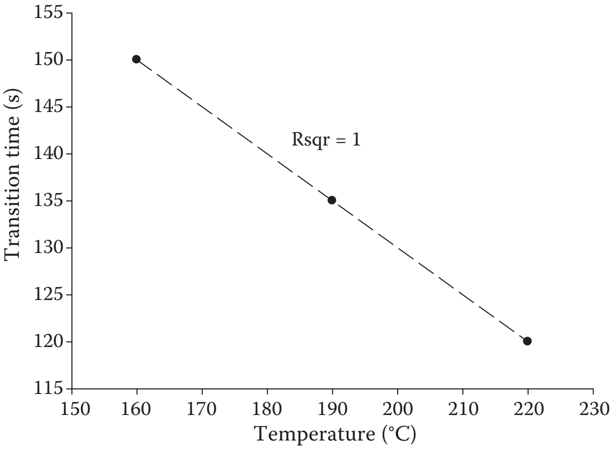

Figure 5. The transition time as a function of isothermal deep-fat frying temperatures (160, 190, and 220°C)

turbulent flow during frying which may collapse the structures, the crust would increase the resistance to releasing water vapour which leads the process to the equilibrium water content of the rapid process. At this point (transition time), the water vapour is released from some tiny local openings. The equilibrium water contents at 160, 190, and 220°C were 35.3, 26.6, and 22.8%, respectively, in this section (Table 2). When the frying proceeds further to a certain extent, the structure changes tremendously to make the water vapour release even harder. This makes the water losses pass the transition point to the 2nd part of the process, the slow process. In this section, the water loss was even harder and few openings can be used to release the water vapour which makes the process move to the 2nd part of the equilibrium water content, C_{inf2}. The equilibrium water contents, C_{inf2}, were in this section 22.7, 9.6, and 5.3%, respectively, at 160, 190, and 220°C. Figure 4 shows the linear relationship between the equilibrium water contents and frying temperature in the two hypothesised processes.

Microstructure. Aguilera *et al.* (2001) report that during frying, starch granules are subjected to rapid pasting, so that they fill the entire surface of the cell without causing any damage. According to Costa *et al.* (2001), crispy surface is developed

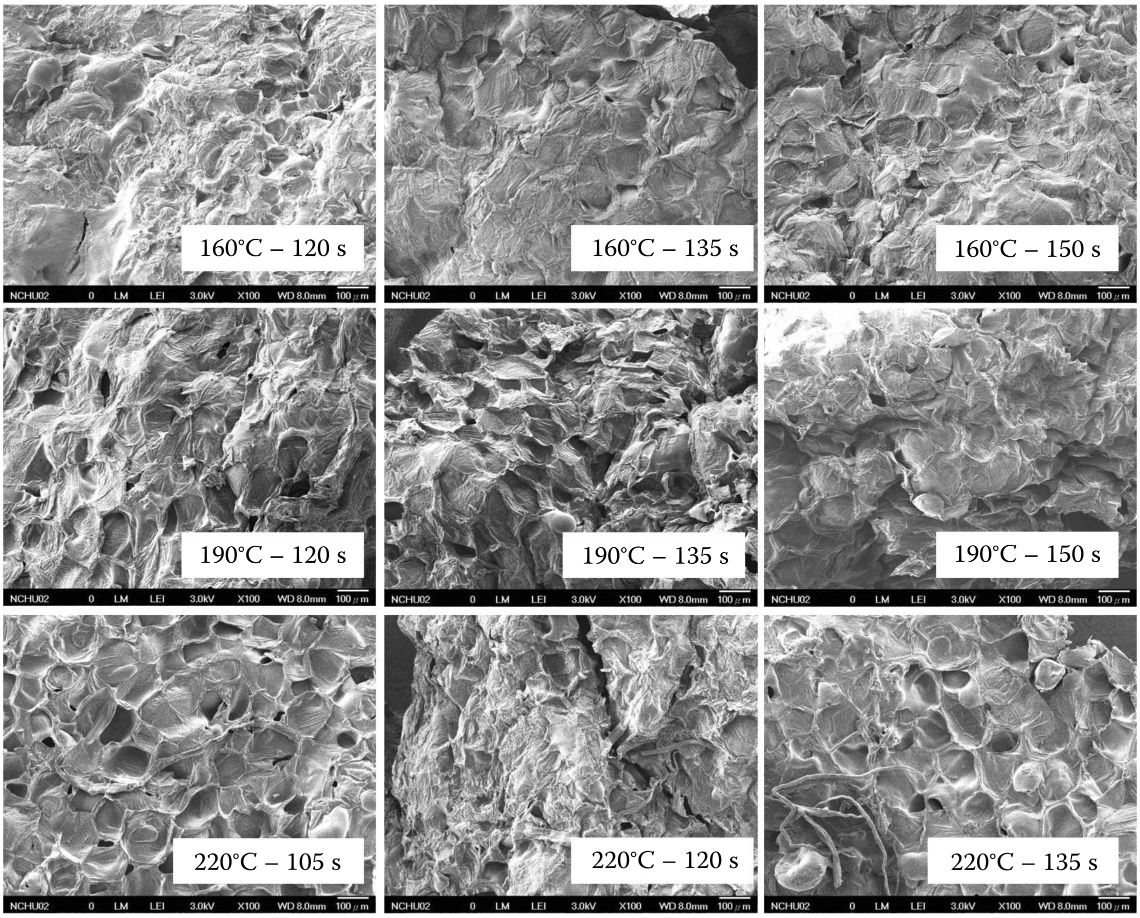

Figure 6. Field emission scanning electron microscope (FESEM) pictures of the surface of a fried potato particulate at 160, 190, and 220°C before and after transition time

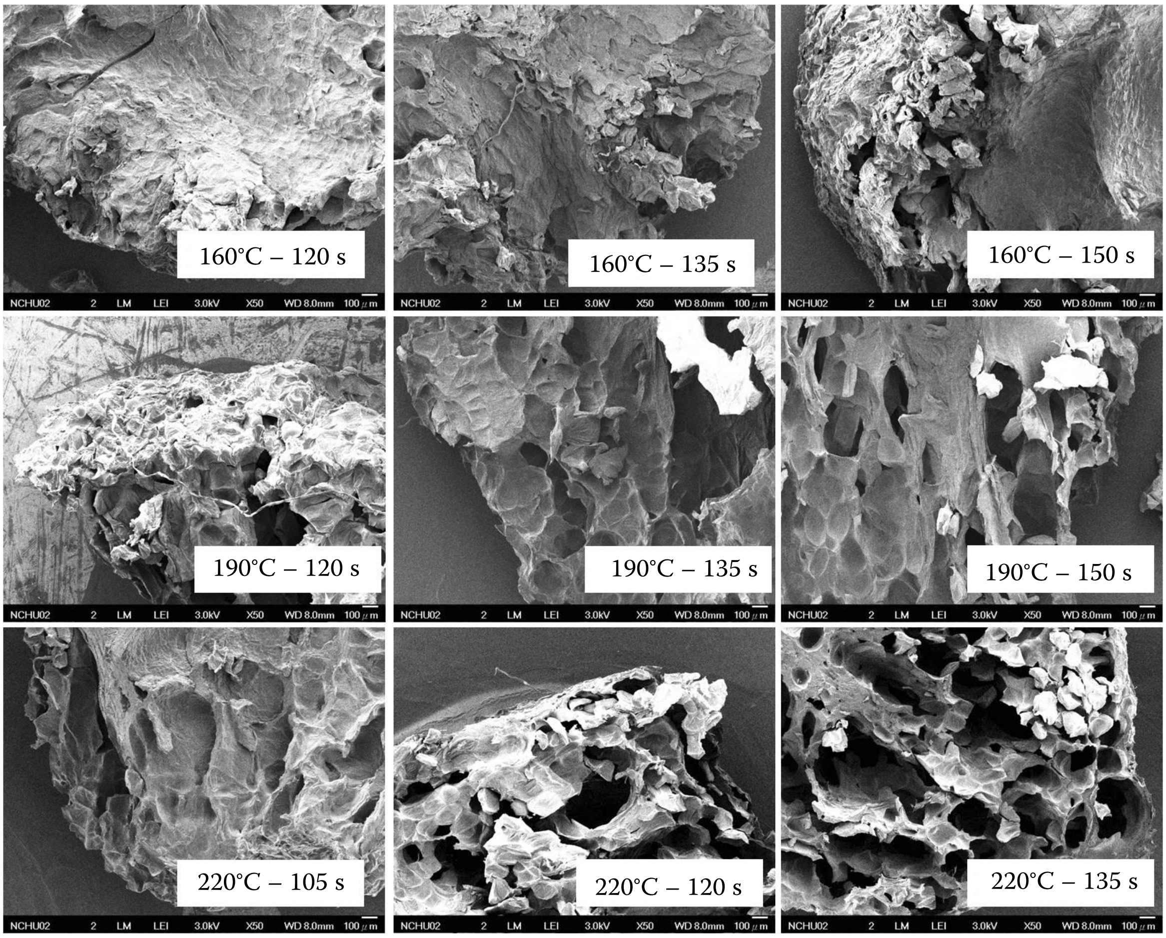

Figure 7. Field emission scanning electron microscope (FESEM) pictures of the cross section of a fried potato particulate at 160, 190, and 220°C before and after transition time

due to the migration of oil into intracellular spaces formed during frying as a result of cell wall shrinkage and water evaporation. The observations of structural changes on the surface and in inner sections of potato particulates are critical to the understanding of crust and oil uptake in fried samples.

Under the high temperatures of frying, starch granules on the surface of potato particulates absorb the water in the inside and begin to swell and gelatinise, producing many bubbles shaping the swollen starch. Cells shrivel due to dehydration and become detached from nearby cells. This process starts from the surface and then extends inside potato particulates. Finally, the volume of cells is reduced and the inside of a potato particulate is detached from the skin, producing many pores. Water content is released through these pores into the frying oil. At the same time, a crispy surface is formed as frying oil permeates into the gaps between cells through the pores. At the end, potato particulates are fried into porous, dry objects with a hard surface (Bouchon & Aguilera 2001; Costa *et al.* 2001; Lisinska & Golubowska 2005; Ziaiifar *et al.* 2008).

Figure 6 shows the surface structure of potato particulates after frying at different temperatures and times observed using FE-SEM. Only round holes without any oil content are left because the samples are first immersed in ether to remove the oil before the structure observation. The irregular bumps in some pictures are caused by gelatinisation of potato starch. Swelling and gelatinisation on the surface of potato particulates become more and more apparent with longer frying times, while the diameter of the round holes gradually shrinks as a result of the cell dehydration, causing the surface structure to become smaller. The same situation occurs with different frying temperatures. However, starch swelling and cell shrinkage are more apparent at higher frying temperatures.

Based on visual observation, Gamble and Rice (1987) postulated that steam in the interior of the product is released through passages formed by weak adhesion between cells which later serve for oil infiltration. Figure 7 shows the cross section of potato particulates observed using FE-SEM, which is different from the surface structure shown in Figure 6. As the frying time increases, the pores in potato particulates become larger and more apparent, indicating a greater loss of water content and more apparent cell separation. We also observed that a hard crust forms at the surface of potato particulates during the frying process, blocking water loss and oil absorption, thus increasing the internal pressure. As water in potato particulates gain more energy and the internal pressure builds up, water breaks through the hard crust and continues to be lost; the internal structure also continues to change. After a longer frying, the internal structure continues to shrink and higher pressure is required for water to break through. When water does break through the structure, it creates greater damage to the internal structure and creates larger pores in potato particulates. With respect to frying, the major damage to the inner cell structure of potato particulates is basically dehydration and shrinkage.

The transition times for the frying temperatures of 160, 190, and 220°C are 150, 135, and 120 s, respectively. Regardless of the frying temperature, there is a significant difference in the pore size before and after the transition time. The pores in the internal structure (Figure 7) of the potato particulates after frying at 160°C are not apparently compared with potato particulates fried at 190 and 220°C, but the size of pores also gradually increases in the course of frying. As the frying time draws near to the transition time, the edges of matrices become more uneven as more shadows appear, which occurs where pores are located. Therefore, we can see that the pores become more apparent as water is evaporated. The pores not only become larger after the transition time for frying temperatures of 190 and 220°C, but also increase in quantity.

Figure 7, which shows the changes in the internal structure, makes it clear that the change in water loss mechanism at the transition time is caused by the higher pressure building up in potato particulates as water seeks a way out. After the transition time, the loss of the water content follows the slow process; water is lost at a slower rate and via a different mechanism than during the fast process.

CONCLUSIONS

Two simultaneous processes, the rapid process and the slow process, were hypothesised to describe the water loss during frying. The two proposed empirical first-order kinetic rate processes proved to fit well the experimental data of the water loss during frying at 160, 180, and 220°C. The effect of temperature on the rate constants, k_1 and k_2, for both two processes was adequately modelled by the Arrhenius relationship. The average activation energy of the rate constants, k_1 and k_2, was 3.91 and 7.74 KJ/mol, respectively, in the range of the frying temperature from 160°C to 220°C. The observations of structural changes on the surface and in the inner section of potato particulates by means of FE-SEM picture are critical. These items of physical evidence support our previous assumption that the mechanisms of the water loss (two-stage rate processes) before and after the transition time are different.

Reference

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