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The analysis of heat and mass transfer during frying of food using a moving boundary solution procedure

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Abstract Heat and mass transfer during frying of food was analysed using the heat conduction equation. The model developed assumes the presence of two regions, the fried and the unfried regions. The heat convected from the oil to the surface of the food is transferred by conduction through the fried region to an evaporating interface. Most of the transferred heat is utilised to vaporise the water at the interface, while the remaining smaller amount is used for sensible heating. The generated water vapour at the interface was assumed to flow in the fried region with minimum resistance, exchanging heat with the solid. The model was tested against some experimental results available for frying of thick and thin potato chips. The agreement between the predicted and measured temperature distribution was reasonable except at the end of the frying period at which the bounded water may vaporise with a different mechanism and oil may penetrate deep into the potato chips. In all the experiments, the centre temperature of the potato chips remained constant at almost 100°C for a long period which gave a good support to the model developed.

List of symbols

- C_p specific heat capacity of the potato, J kg^{-1} K^{-1}
- E half thickness of the potato chip, m
- h convection or boiling heat transfer coefficient, J s^{-1} m^{-2} K^{-1}
- k thermal conductivity of the potato, J s^{-1} m^{-1} K^{-1}
- n space increment
- N number of spatial increment in the crust and core phases
- m time increment
- t time, s
- T temperature, °C
- y position from the surface of the chip, m
- Y position of the interface separating the core and crust regions, m

Greek symbols

- α thermal diffusivity of potato, m^2 s^{-1}
- ε initial mass fraction of water in the potato, dimensionless
- θ temperature in excess of the boiling temperature (T-100), °C
- Δ increment
- ρ density of potato, kg m^{-3}
- λ_w latent heat of vaporisation of water, J kg^{-1}

Subscripts

- b bounded water
- co core
- cr crust
- o oil
- s surface of the chip or solid potato
- v vapour
- w water

1 Introduction

Immersion frying is a common and effective way of cooking food using hot oil, due to the relatively high cooking temperature that can be achieved. It is estimated [1] that over 250 million kilogram of oil and fat is consumed yearly in the USA for only potato chip production. During the frying process, simultaneous heat and mass transfer occur leading to the removal of water from the food and the penetration of oil in it. It is important to understand the mechanism of water removal and to predict the temperature distribution within the food as both affect the final quality of the fried food. This is of special importance in the frying of potato chips and French fries as the quality is very sensitive to the frying process. Good understanding of the heat and mass transfer during frying would help in optimising the manufacturing processes with regards quality and energy consumption.

There is a strong evidence that most of the oil absorbed by the potato chips occurs during the cooling period of the chips or may be at the late stages of the frying. Moreira et al. [2] have shown that out of the total oil absorbed by the tortilla chips only 20% is absorbed during frying, the remaining being absorbed after frying. It is expected that vigorous boiling of the water generates vapour blanket that may prevent oil from penetrating into the pore structure of the food. As water is depleted the chance of the oil entering the potato chips increases. If the oil penetration is limited during most of the frying period, then the water vapour transfer may be assumed independent of oil transfer. Such

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assumption simplifies the analysis of heat and mass transfer during frying.

Models developed to describe the mechanism of heat and mass transfer during frying vary largely with regards to their assumptions made. The developed models may be classified into two types: (a) The single phase model and (2) The two-phase or moving boundary model. Dincer [1] has employed the single phase model by solving the diffusion equation for both heat and mass transfer. He assumed that there is no effect of mass transfer on heat transfer and vice versa, which enabled him to decouple the heat and mass diffusion equations and hence obtained an analytical solution. The model was used to generate correlations for the heat and mass transfer coefficients between the oil and food products of different geometry. Mittelman et al. [3] have also proposed a semi-empirical relationship for heat and mass transfer during frying. It was found that the rate of frying (expressed by rate of water evaporation) was proportional to the square root of frying time and the difference between the oil temperature and the boiling temperature of water. These observation are in support of the existence of a moving evaporating interface similar to what is usually observed during melting and solidification of materials [4, 5].

Farkas et al. [6, 7] have developed a very comprehensive model to describe heat and mass transfer during frying. They used a two-phase model, assuming that evaporation occur at a moving interface. There is a clear similarity between such process and processes involving melting and solidification. The first well known solution to the problem of heat transfer with moving boundary was that given by Neumann, as presented by Carslaw and Jaeger [8]. The analytical solution of the heat conduction was limited to simple boundary conditions. Later, different investigators [4, 5] have applied the finite difference method of Murray and Landis [9] for studying the process of melting and solidification of paraffin waxes. Farid et al. [10] have also developed an effective heat capacity method that can be used for two and three dimensional geometry.

The frying process, involving heat and mass transfer, is more complex than freezing. Farkas et al. [6, 7] have assumed the existence of two regions, separated by an interface: the core (unfried) and crust (fried) regions. Heat is transferred from the hot oil to the interface via the crust region and water is evaporated at the moving interface at a temperature of 100°C. The unsteady state heat conduction equation was used to describe heat transfer in both regions. In the core region, mass transfer of water was assumed to be governed by Fick's law of diffusion. For more details about the model used we refer to the above mentioned two papers. The sets of equations describing heat and mass transfer in the core and crust regions were solved using finite differences and the results were compared with some experimental data. It was possible to predict the temperature distribution within 25.4 mm thick potato slab made out of rehydrated dried potato mixture. The prediction of the model for the temperature distribution, water content, and thickness of the crust region was reasonable. Results showed very significant temperature distribution within the crust region due to its low thermal conductivity. Accordingly, rate of heat and mass transfer were observed to decrease with time during the frying process.

The model developed by Farkas et al. [6, 7] is comprehensive but the computational time required is very large as reported by them, suggesting the necessary of carrying some simplifications to the model in future. The model has been tested against experimental measurements of one-dimensional heat transfer during frying of 25.4mm thick potato chips. However, the comparison between the experimental results and theoretical prediction was given for limited time of frying (960 s). At such time only 34% of the water was removed. Although such a condition may be practical for frying of French fries, such frying process is far from being complete for the frying of thin potato chips. The model has not been tested for thin potato chips (in the order of few mm). It is also believed that the extension of the model to multi-dimensional geometry is difficult, especially with regards the required computation time.

It is the objective of this paper to develop a simple, effective, moving boundary model, based on our pervious experience in the melting and solidification of materials [4, 5]. The model developed in this paper was tested against some experimental results of one dimensional heat transfer during frying of potato chips of different thicknesses. The model was also tested against the experimental measurements of Farkas et al. [7] for thick potato chips. The effect of the presence of some bounded water is discussed.

During the course of writing this paper, Chen and Moreira [11] have published a refined model for frying of tortilla chips. Although the model included the transport of the oil in the potato, the heat associated with the oil transport was ignored. The model was not a moving boundary model, as vapour was assumed to diffuse from the whole body of the chips. The agreement between the model and their experiments was good. However, the model contained too many parameters such as the diffusion coefficient and mass transfer coefficient in addition to the heat transfer parameters. There is a basic difference between such model and the moving boundary models, as it is discussed in the following section.

2 Theoretical

The potato chip was assumed to be an infinite slab composed of porous solid structure (packed with starch molecules) filled with water. The extension of the model to multi-dimensional geometry, for frying of other types of food, is possible. Heat is transferred from the hot oil to the surface of the potato by natural convection during the sensible heating then by convective boiling during the evaporation period. The initial sensible heating of the slab is governed by the unsteady state heat conduction equation (1), assuming negligible water evaporation during the period. The effects of shrinkage and oil penetration were ignored in the analysis.

After the surface temperature reaches the water boiling temperature of 100°C, water starts to evaporate and a thin layer of crust is formed. The evaporation is assumed to occur at a temperature of 100°C at the penetrating interface. It is assumed that water vapour diffuses freely through the crust region. This is reasonable since vapour flow is expected to be governed by bulk flow of vapour according to Darcy's Law rather than that by diffusion as usually assumed in the literature. As the interface reaches the center of the potato chip all the water (except the bounded water) is assumed to have been evaporated and sensible heating of the solid chip will occur, based on the heat conduction equation.

In developing this model, the effect of water diffusion in the core was ignored. It is believed that the high heat transfer rate during frying gives little chance for the water to diffuse in the core. Arzan et al. [12] have applied the moving boundary analysis for a drying process. Water diffusion was also ignored in their analysis which has not been supported by any experimental measurements. It is reasonable to believe that the effect of water diffusion may be ignored in high temperature processes such as frying and high temperature drying.

The finite difference method of Murray and Landis [9], used previously by Farid et al. [4, 5] to describe melting and solidification is used in this paper to describe heat transfer during frying. The heat conduction equation:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial y^2} \tag{1}$$

Equation (1) is first solved for the core region as a single phase. Then it is solved for both the core and the crust regions, with the following initial and boundary conditions:

$$t = 0 \quad T = T_{\mathrm{i}} \tag{2}$$

$$y = 0 \quad h(T_{\mathrm{o}} - T_s) = -k_{\mathrm{cr}} \frac{\partial T_s}{\partial y} \tag{3}$$

$$x = E/2 \quad \frac{\partial T_{\mathrm{co}}}{\partial y} = 0 \tag{4}$$

$$y = Y_m \quad T_{\mathrm{co}} = T_{\mathrm{cr}} = 100^\circ\mathrm{C} \tag{5}$$

$$y = Y_m \ \rho_{\mathrm{co}} \lambda_{\mathrm{w}} \varepsilon \frac{\mathrm{d}Y_m}{\mathrm{d}t} = k_{\mathrm{cr}} \frac{\partial T_{\mathrm{cr}}}{\partial y} - k_{\mathrm{co}} \frac{\partial T_{\mathrm{co}}}{\partial y} \tag{6}$$

where "cr" and "co" refer to the crust and core regions respectively and Y_m refer to the interface position, with other parameters defined in the nomenclature. Equation (4) implies that the potato chip is fried symmetrically.

The two regions were divided into equal number of space divisions. As the frying proceed, the thickness of the crust region increases and hence the space increment width will get bigger. On the other hand, the increment width of the core will decrease as frying progresses. Using an explicit finite difference formulation the following two nodal equations are obtained and used to calculate the dimensionless temperature in both regions:

in the crust region:

$$\begin{aligned}\Theta_{n,m+1} = {} & \Theta_{n,m} + n(\Theta_{n+1,m} - \Theta_{n-1,m}) \\ & \times (Y_{m+1} - Y_m)/(2Y_m) \\ & + \alpha_{\mathrm{cr}} \Delta t N^2 (\Theta_{n-1,m} - 2\Theta_{n,m} + \Theta_{n+1,m}) Y_m^2\end{aligned} \tag{7}$$

in the core region:

$$\begin{aligned}\Theta_{n,m+1} = {} & \Theta_{n,m} + (2N - n)(\Theta_{n+1,m} - \Theta_{n-1,m}) \\ & \times (Y_{m+1} - Y_m)/(E - Y_m) + \alpha_{\mathrm{co}} \Delta t N^2 \\ & \times (\Theta_{n-1,m} - 2\Theta_{n,m} + \Theta_{n+1,m})/E - Y_m)^2\end{aligned} \tag{8}$$

The interface position is calculated from the following equation:

$$\begin{aligned}Y_{m+1} = {} & Y_m + \{\Delta t/(\rho_{\mathrm{co}} w \lambda_w (1 - w_b))\} \\ & \times [(0.5 k_{\mathrm{cr}} N/Y_m)(\Theta_{N-1,m} - 4\Theta_{N,m}) \\ & + 0.5 k_{\mathrm{co}} N (\Theta_{N+3,m} - 4\Theta_{N+2,m})/(E - Y_m)]\end{aligned} \tag{9}$$

The mentioned formulations represent the simplest form of equations that may describe heat and mass transfer in frying. The heat exchange between the generated vapour and the crust region is small as the sensible heating is always small compared to the latent heat of vaporisation. Using Steam Table, our calculation shows that the heat exchange between the vapour and the solid crust represent less than six percent of the total heat. To include this term, the following equation will replace Eq. (1):

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial y^2} - \frac{\rho_{\mathrm{v}} C p_{\mathrm{v}}}{\rho_{\mathrm{cr}} C p_{\mathrm{cr}}} \frac{\mathrm{d}Y}{\mathrm{d}t} \frac{\partial T}{\partial y} \tag{10}$$

The following finite difference formulation may replace equation (7):

$$\begin{aligned}\Theta_{n,m+1} = {} & \Theta_{n,m} + n(\Theta_{n+1,m} - \Theta_{n-1,m}) \\ & \times (Y_{m+1} - Y_m)/(2Y_m) \\ & + \alpha_{\mathrm{cr}} \Delta t N^2 (\Theta_{n-1,m} - 2\Theta_{n,m} + \Theta_{n+1,m})/Y_m^2 \\ & - 2(N/2Y_m)(\rho_{\mathrm{v}} C p_{\mathrm{v}}/\rho_{\mathrm{cr}} C p_{\mathrm{cr}})[Y_{m+1} - Y_m] \\ & \times [\theta_{n-1,m} - \theta_{n+1,m}]\end{aligned} \tag{11}$$

The results of the computation using Eq. (7) or (11) were very similar. The computation has been done in five steps:

1. Sensible heating of the potato chip until its surface temperature reaches the evaporating temperature. Equation (1) is solved with the initial and boundary equations (2)–(4), using explicit finite difference formulation with a time increment controlled by stability requirements. Physical properties of the core were used with the value of the convective heat transfer coefficient reported in the literature and shown in Table 1.

Table 1. Physical properties of the potato chips

Property	Crust region	Core region
Density (ρ)	386 $\mathrm{kgm^{-3}}$	1132 $\mathrm{kgm^{-3}}$
Thermal conductivity (k)	0.14 $\mathrm{Jm^{-1}K^{-1}s^{-1}}$	0.655 $\mathrm{Jm^{-1}K^{-1}s^{-1}}$
Specific heat capacity (Cp)	1790 $\mathrm{J\ kg^{-1}K^{-1}}$	3450 $\mathrm{J\ kg^{-1}K^{-1}}$
Parameter	**Value**	
Convection coefficient (h_c)	250 $\mathrm{Jm^{-2}K^{-1}s^{-1}}$	
Boiling coefficient (h_b)	500 $\mathrm{Jm^{-2}K^{-1}s^{-1}}$	
Initial water content (ε)	0.714 (ref. 7), 0.8 (ref. 15)	

2. The numerical finite difference method requires the computation to start with the presence of two regions. Hence an approximate estimate for the time required to form a thin layer of crust was necessary. This has been done by assuming that the heat transferred from the hot oil to the surface of the potato chip is totally utilised for evaporating the water from the thin layer of the potato. The temperature distribution within this layer was assumed linear. The magnitude of error introduced from this estimate is very small if the thickness chosen is reasonably small. However, extremely small initial thickness should be avoided, otherwise the computational time will be large due to the stability requirements of the explicit method. Accordingly, the selected initial layer thickness of the crust region was set to 1% to 2.5% of the potato chip thickness.

3. For the longer period of frying (evaporation period), Eq. (1) is solved for both the crust and core regions with the boundary and initial conditions stated in Eqs. (2)–(6). The finite difference formulations expressed by Eqs. (7)–(11) are used in the computation. Heat is assumed to transfer from the hot oil to the surface of the potato chip by convection boiling process, with a coefficient higher than that used in steps 1 and 5.

4. When the evaporating surface approach the centre of the chip (a distance equivalent to 1–2.5% of the chip thickness), the computation in step 3 is stopped and the time required to evaporate the remaining water is estimated from an energy balance as done in step 2.

5. The computation for the sensible heating of the fried potato is done by solving equation (1) with its boundary and initial conditions, using the physical properties of the crust region.

The time increment in all the steps was automatically adjusted according to the stability requirement. This caused the computations to be slow during the initial and final periods of step 3.

3
Physical properties of the core and crust regions

Physical properties of fresh potato and the completely fried chips were used to represent the properties of the core and crust regions. The values reported by Farkas et al. [7], as measured by different investigators, are used in our simulation. However, the reported value of the crust specific heat capacity was not realistic one. Also the density of the fresh potato (core region) was calculated as follows:

$$\rho_{co} = \varepsilon\rho_w + (1-\varepsilon)\rho_s \tag{12}$$

substituting the values of porosity and solid density reported by Farkas et al. [7] (Table 1) into Eq. (12) gives a value of 1132kgm^{-3} for the core density.

The reported value of specific heat capacity of the crust (3050 Jkg^{-1}K^{-1}) is very high. It is only slightly lower than the value measured for the core (3450 Jkg^{-1}K^{-1}). A much smaller value is expected for the crust specific heat capacity since the water which has large heat capacity is replaced by the low specific heat capacity of water vapour. Schmalko et al. [13] have measured the specific heat capacity for twigs of yerba mate with different water contents. They reported the following equation:

$$Cp = 1790 + 2360\varepsilon \tag{13}$$

where ε is the water contents expressed in mass fraction. Using the value reported by Farkas et al. [7] for the initial water content of 71.4wt% (2.5kg water/kg solid), Eq. (13) gives a value of Cp equal to 3476 Jkg^{-1}K^{-1}, which is very close to the value of 3450 Jkg^{-1}K^{-1} reported for potato by Farkas et al. [7] Since the linear Eq. (13) was found to predict values of Cp for water and for potato chips with a water content of 71.4wt% then it may be used for the approximate estimation of the specific heat capacity of the fried potato (crust region). Equation (13) predicts a value of 1790 J kg^{-1}K^{-1} for the specific heat capacity at zero water content.

Donsi et al. [14] have measured the thermal conductivity of potato at different water contents and obtained an equation that give an estimate of about 0.14 Jm^{-1}K^{-1}S^{-1}) for the thermal conductivity of potato at zero water content. This value which is used in our simulation is slightly higher than the value of 0.12 Jm^{-1}K^{-1}S^{-1} reported by Farkas [13]. The effect of final oil and water content in the fried potato chips could be significant on the measured value of thermal conductivity.

The values of the physical properties of the core and crust regions, used in the simulation, are shown in Table 1. These physical properties were also used in the prediction of the experimental results of Wolf [15] except for the initial water content which was 80% . The measured final water content was 4 to 5wt% which was considered as bounded water in the simulation program.

4
Experimental

For the details of the frying measurements of Farkas et al. [7], we refer to the mentioned reference. The frying measurements reported by Wolf [15] were carried out using a domestic deep fryer, which was insulated to minimise temperature fluctuation. The assumption of constant oil temperature was true since the frying of a single potato chip produced very little temperature change in the oil even when the electrical heater of the fryer was turned off. A calibrated, K-type teflon coated thermocouple was used to measure the oil and centre temperature of the chip. It was very difficult to measure the surface temperature as the thermocouple tends to measure the oil temperature rather than the surface temperature of the chip. The potato chips of different thicknesses were cut with a sharp knife and their average thicknesses were measured using a vernier calliper. The potato chip, fixed by a specially designed holder, was immersed in the oil when its temperature reached 180°C and left until the centre temperature approached 180°C. Initial and final water content were measured for all the potato chips. Silica gel was left for two weeks with the fried potato chips to insure complete removal of water.

A data logging system with a PC was used to record and analyse the measured centre temperature as frying proceed.

5
Results

Figure 1 shows model prediction for the crust thickness of a 25.4 mm thick potato chip fried at 180°C and 160°C, as measured by Farkas et al. [7] The agreement between our developed simple model and the experimental results is reasonable and similar to that shown by the detailed model developed by Farkas et al. [6, 7]. The measured and predicted temperature distribution during frying at 180°C is shown in Fig. 2, for two different frying times of 240s and

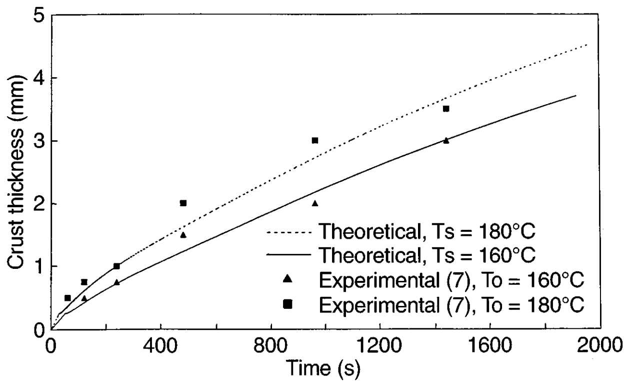

Fig. 1. Model prediction for the measurements of crust thickness of thick potato chips

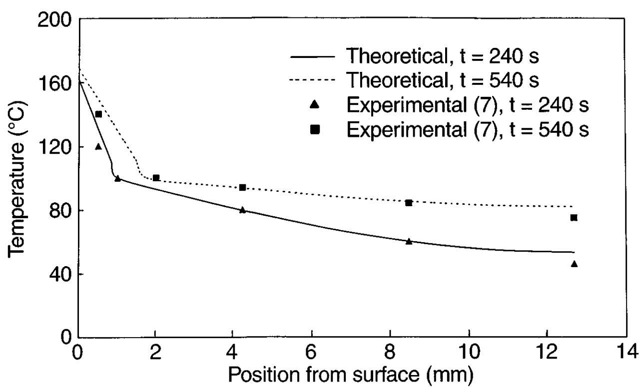

Fig. 2. Model prediction for the temperature distribution in thick potato chips fried at 180°C

540s. The agreement between the measured and predicted values is good, realising the practical difficulty usually associated with such type of measurements. The steep change in temperature with position until it reach 100°C, as predicted experimentally and theoretically, gives strong support to our moving boundary model. This observation is very similar to what has been shown in the literature for melting and freezing of materials [4].

In our model water content in the potato chips is estimated directly from the crust thickness. Hence the effect of frying temperature on the water content is similar in magnitude to that shown in Fig. 1. Farkas et al. [7] have shown a good agreement between their model prediction and one of the experiment. However, their experiments show significant effect of the frying temperature on the water content, while the model show very little effect.

The measurements of Farkas et al. [7] were terminated when the centre temperature approach 100°C and hence our model can not be fully tested using these measurements. The available measurements of Wolf [13] for deep frying at 180°C of thin potato chips with different thicknesses were used for this purpose. In these experiments, frying was continued until the centre temperature reaches the oil temperature. These data can be used to test the model in the three stages of frying: the sensible heating period, the evaporation period, and the sensible heating of the fried potato chips. Fig. 3 shows model prediction for the center temperature of the 3 mm thick potato chips. The seven experimental tests show significant variation which could be mainly due to the difficulty in fixing the thermocouple at the centre of the chips. The problem is more serious with the 3 mm thick chips when compared to chips of larger thicknesses. However both the experimental measurements and theoretical prediction agree in showing rapid increase in the centre temperature of the chips until it reaches 100°C. Following that period, the model predicts a constant centre temperature until the water is completely depleted after which the centre temperature rises very rapidly. The experimental results also show a distinct constant temperature period supporting the model. However, the constant center temperature was always higher than the theoretical value of 100°C. This deviation of centre temperature from the boiling temperature of water

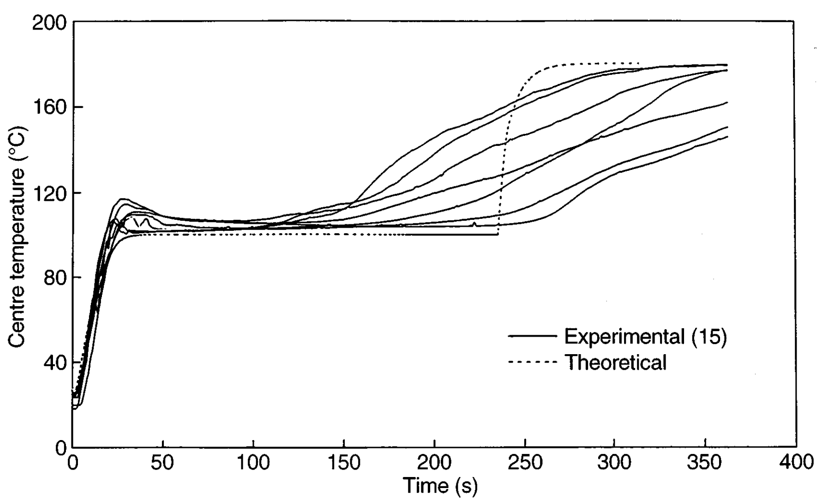

Fig. 3. Model prediction for the measured centre temperature of 3 mm thick potato chips fried at 180°C

could be due to oil migration through the potato chips. Figures 4 and 5 show that the deviation of the measured centre temperature from 100°C decreases as the thickness of the potato chips increases. With very thick potato chips as that used by Farkas et al. [7] the measured centre temperature was always 100°C, suggesting negligible oil migration during the period of measurements. In these experiments, the frying process was stopped while water evaporation was vigorous enough to prevent oil penetration.

Figures 3–5 show an increase in the measured centre temperature of the potato chips up to 120°C at the end of the sensible heating, followed by rapid decrease to the constant temperature period. This increase diminished as the potato chip thickness increased. The most likely reason for such observation is the early oil migration which is usually stopped as soon as evaporation becomes vigorous.

At the end of the evaporation period, the model predicts sharp increase in the centre temperature while the experiments show a gradual increase. Figures 3–5 show that this increase vary significantly between samples of the same thicknesses fried under the same conditions. This may be the major limitation of our model, however, this would be the case with any moving boundary model including the detailed model of Farkas et al. [6, 7]. The model predicts the true centre temperature of the chip, while the measured temperature is an average value within a distance of one thermocouple radius. If this is considered, the model would show less sharp increase in the center temperature. However, even with such consideration the model does not properly describe what happen after most of the water is evaporated. It is believed that the partial and gradual evaporation of the bounded water and oil penetration may be the main reasons for the slow change in the centre temperature observed throughout all the experiments. The non moving boundary models, being diffusional, describe this period better but is not expected to describe the long period of constant temperature as may be seen from the results of Chen and Moreira [11]. In future work, we shall develop the model further to take into account the diffusion period following the constant temperature period.

Figure 5 demonstrates the strong effects of the crust thermal conductivity on the frying time, while Fig. 6 shows its effects on the crust thickness and water content. It is the only critical physical property that must be determined accurately for a reasonable prediction of the frying process. The effects of the physical properties of the core were tested and found insignificant. Due to the high convection heat transfer coefficient during frying the surface temperature of the chip approaches the oil temperature fast and is not affected very much by other parameters.

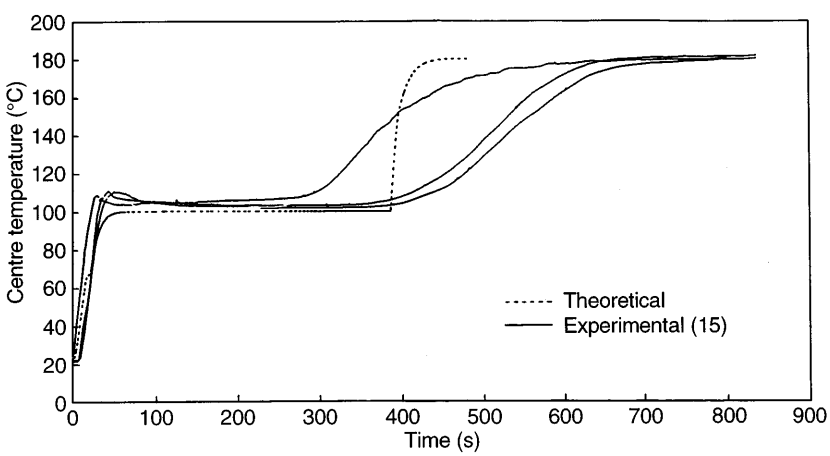

Fig. 4. Model prediction for the measured centre temperature of 4 mm thick potato chips fried at 180°C

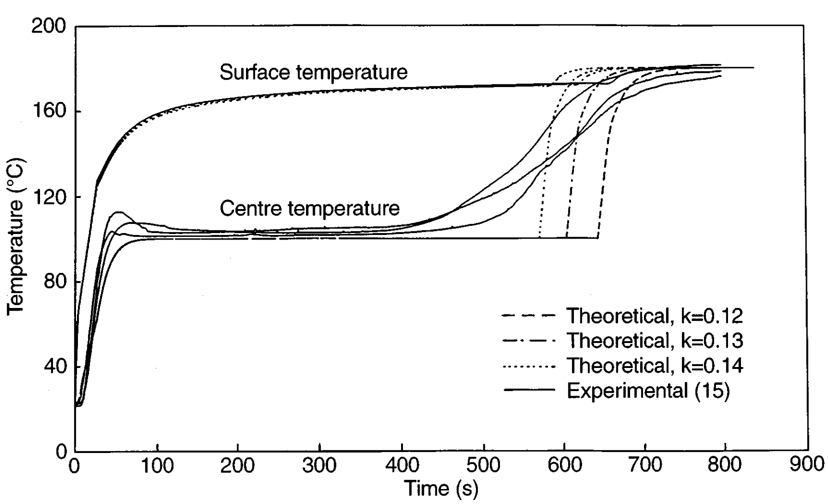

Fig. 5. Effect of crust thermal conductivity on the surface and centre temperature of 5 mm thick potato chips fried at 180°C

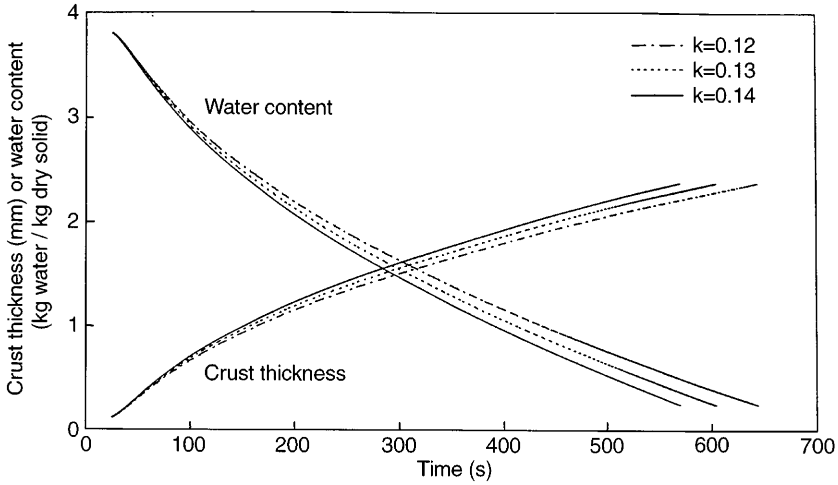

Fig. 6. Effect of crust thermal conductivity on the crust thickness and water content of 5 mm thick potato chips fried at 180°C

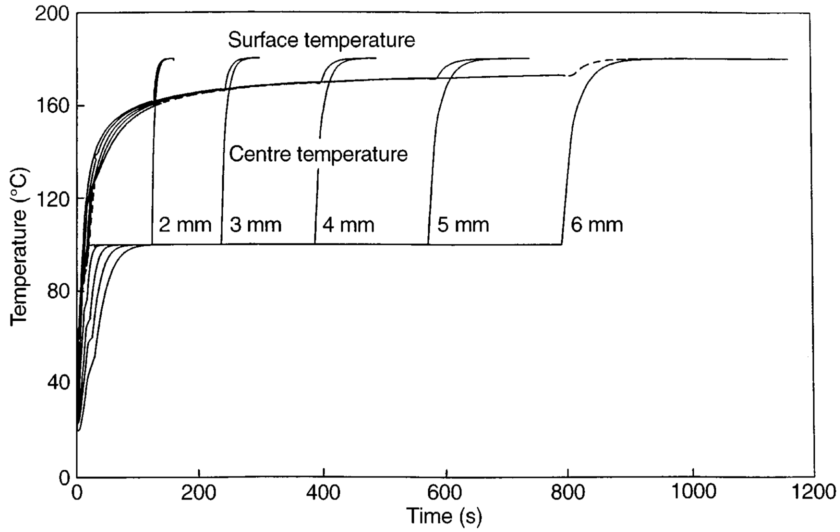

Fig. 7. Model prediction for the surface and centre temperatures of different thickness potato chips fried at 180°C

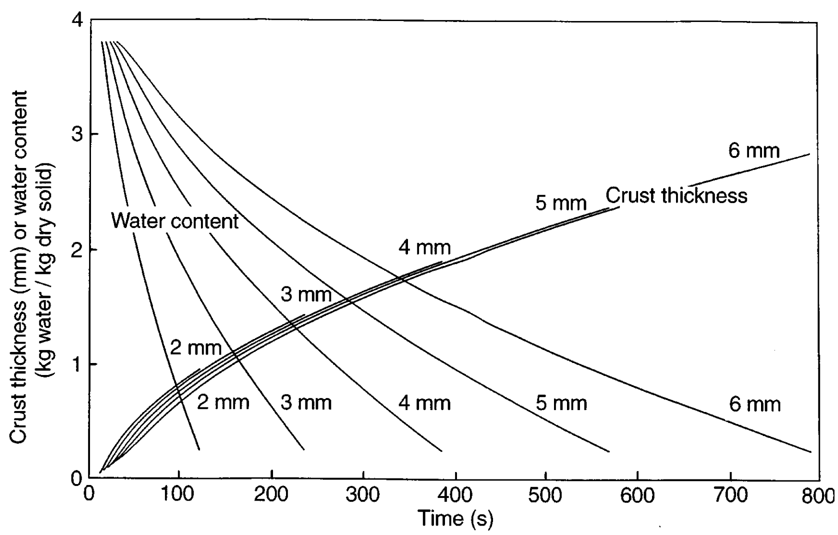

Fig. 8. Model prediction for crust thickness and water content of different thickness potato chips fried at 180°C

Model predictions of the centre temperature, surface temperature, crust thickness, and water content for potato chips of different thicknesses, fried at 180°C are shown in Figs. 7 and 8. Figure 8 shows that crust thickness was affected only little by the chips thickness used as the process of frying is mainly controlled by heat transfer through the crust region. Figures 9 and 10 show the effect of doubling the boiling heat transfer coefficient on the

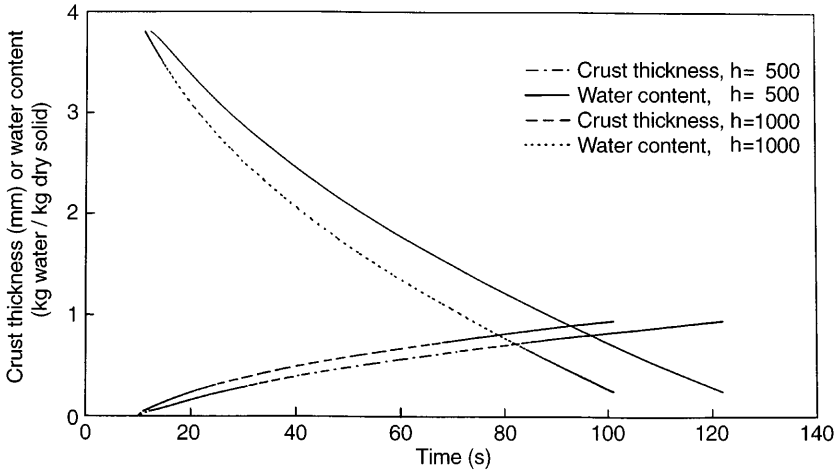

Fig. 9. Effect of using higher boiling heat transfer coefficient on the prediction of crust thickness and water content in 2 mm thick potato chips fried at 180°C

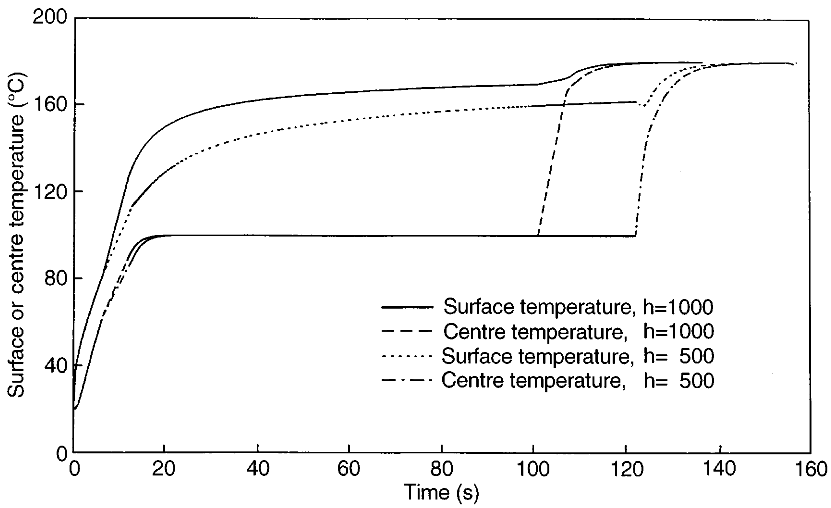

Fig. 10. Effect of using high boiling coefficient on the centre and surface temperatures of 3 mm thick potato chips fried at 180°C

crust thickness, water content, center and surface temperatures of the chip.

It is to be noted that the model has been extensively tested regards its numerical stability. The selected number of division was 12. However, when the number was reduced to 8 very little effect on the results was found.

6 Conclusions

A moving boundary model was developed to describe the heat and mass transfer that occur during frying of foods. The simplified model, unlike other moving boundary models, require minimum parameters making it easy to apply to most practical situations. Sensitivity analysis showed that the fried crust thermal conductivity is the only important parameter required by the model. The model is far simpler than the previously developed model. It describe the short sensible heating period and the relatively long evaporation period well as may be seen from the comparison with some the experimental measurements. However, the model fails to describe the late period of frying in which the bounded water may start to evaporate with different mechanism. The sharp increase in the centre temperature at the end of the heating period is typical of any moving boundary model.

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