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Original Article

Simulation of the heat and mass transfer processes during the vacuum frying of potato chips

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Abstract

A fundamental two-dimensional model to predict the heat and mass transfer that occur during the vacuum frying of potato chips was solved using the Finite Element toolbox in MATLAB 6.1. The simulation of the heat transfer process included the convection of heat from the surface to the product, the conduction of heat into the product, and a loss of heat using the heat source term representing evaporation. The mass transfer process was divided into two periods: (1) water loss and (2) oil absorption. The first scenario included a diffusion term and a source term. The source term represented the convection and evaporation of water from the product. For the second period, the diffusion term represented the gradual absorption of oil through capillary diffusion.

From the simulation, a good agreement between the experimental data and the predicted values was obtained. From the heat transfer model, the rapid increase in temperature of the product toward the boiling point of water (at the associated pressure) followed by its steady increase toward the temperature of the oil was validated. Furthermore, by separating the rate of moisture loss into two parts to represent the constant rate and falling rate period of drying, the model was able to predict an initial period of rapid moisture loss followed by a decreasing rate of moisture loss. The simulation also demonstrated the formation of the crust and the gradual movement of the crust inward. Finally, using two sets of diffusion coefficients that correlated to the two schemes of moisture loss, the model predicted the rapid flux of oil into the product during the constant drying stage, followed by a small amount of oil absorption into its interior once the crust had been established.

Keywords: Modeling, finite element, vacuum frying, frying, oil absorption, fruits and vegetables snacks

1. Introduction

Due to the rising health concern and the trends toward healthier snacks, vacuum fried fruits have become a common product that can be found in local markets. While many people are still unfamiliar with this snack, a wide range of fried fruits are now offered on local market shelves, ranging from fried bananas, jackfruits, pineapples, and pumpkins, just to name a few. Most of these snacks are imports from outside Asian countries, such as Malaysia, Vietnam, and China, but an increasing number of Thai food processing companies are now offering these tasty snacks. Nonetheless, the vacuum frying process, similar to the atmospheric frying process, is quite complicated, involving coupled heat and mass transfer through a porous media, crust formation, product shrinkage and expansion, and so forth. These mechanisms all contribute to the difficulties in predicting physical and structural appearance of the final product. Hence, a better understanding of the frying mechanism and the heat and mass transport phenomena would be useful to food processors in order to produce and develop new fried and vacuum fried snack foods for growing allegiance of healthy consumers.

For the past 10 years, much research has been involved in the modeling of the heat and mass transfer that

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occurred during the atmospheric frying process. During frying, the heat from the oil is convected to the product surface and is then conducted to the product's center, thus increasing its temperature. Water evaporates as the product reaches the boiling-point temperature. This process is generally considered a Stephan type heat transfer problem, which is characterized by the presence of a moving interface that divides two regions of physical and thermal properties (Farkas, Singh & Rumsey, 1996a).

In their study, Farkas, Singh, and Rumsey (1996a, b) provided a more detailed model of temperature and moisture transport in deep fat frying. They provided separate equations for two regions: (1) the crust and (2) the core, with a moving boundary. The proposed model included-pressure driven flow in the crust for the vapor phase, but did not include diffusion flow in the crust region or pressure-driven flow of liquid and vapor in the core region. The model also did not consider the oil phase.

In other studies, Rice and Gamble (1989) and Dincer and Yildiz (1996) considered only energy and moisture diffusion. Ateba and Mittal (1994) considered separate diffusion equations for energy, total moisture, and oil phases, without any evaporation term in the energy or the moisture equation. Moreira *et al.* (1995) included evaporation at the surface (but not internal), and only considered energy and moisture diffusion while ignoring the oil phase transport in the model.

A more complete model was developed by Ni and Datta (1999), who considered a multiphase porous media model based on the approach of Whitaker (1977) which included the significance of pressure-driven flow for the oil, vapor, and air phase. They suggested that this type of model is appropriate for the study of deep fat frying because it includes all transport mechanisms (i.e., molecular diffusion, capillary, and pressure driven flow), while all the phases (i.e., oil, water, vapor, and air) keep their individuality.

Yamsaengsung and Moreira (2002a, b) developed and solved a set of coupled heat and mass transfer equations based on Ni and Datta's approach (1999). The authors took into account the structural changes and solved the equations using 2-D Finite Element formulation. The model presented the changes in water saturation, oil saturation, temperature, and pressure as a function of time.

Even though these studies have shed some light on the transport phenomena during the atmospheric frying process, more reliable experimental data is needed for verification of the results (such as temperature, moisture, and oil profiles). In the same way, the study of these transport mechanism have led to the investigation on the effect of vacuum frying on the transport processes. For instance, several studies have shown that less oil is absorbed during the vacuum frying process (Garayo and Moreira, 2002; Krupanyamat and Bhumiratana, 1994; Choodum and Rojwatcharapibarn, 2002; and Yamsaengsung and Rungsee, 2003). It has been suggested that the pressure difference between the internal pressure of the product and the vacuum pressure of the fryer help to reduce the amount of surface oil present at the end of the frying process, which in turn limits the total amount of oil absorbed.

Another important advantage of vacuum frying is the reduced temperature which helps to maintain the natural coloration of the product while minimizing the loss of vitamins and minerals. In atmospheric frying, products are generally fried at 160-190 C, and water inside the product evaporates at approximately 100 C depending on the presence of dissolved components; on the other hand, under vacuum, the boiling point of water can be reduced to as low as 35-40 C, thus the frying temperature can be as low as 90-100 C. Shyu and Hwang (2001) found that the optimum conditions for the frying of apple chips were at a pressure of 3.115 kPa, a frying temperature of 100-110 C, a frying time of 20-25 min, and a concentration of immersing fructose solution of 30-40%.

In addition, Garayo and Moreira (2002) found that potato chips fried under vacuum conditions (3.115 kPa and 144 C) had more volume shrinkage and were slightly softer, and lighter in color than the potato chips fried under atmospheric conditions (165 C). Yamsaengung and Rungsee (2003) also found that compared to atmospheric frying, vacuum fried potato chips retained in a more intense flavor and color. Therefore, with its many advantages, it is important to investigate the heat and mass transfer mechanisms during the vacuum frying process. This research presents the sets of models used to describe of the process including the heat and mass transfer equations along with the simulated results using the Finite Element Toolbox in the MATLAB 6.1 software.

2. Model Development

2.1 Description of the Transport Phenomena

The drying and frying processes are very similar and many models have been developed to describe and predict the two systems. The basic energy and mass governing equations are very much the same. The differences in the models usually come in the system in which the model is describing. In each case, assumptions, boundary conditions, transport mechanisms, and physical properties for each system will vary (Yamsaengsung and Moreira, 2002a). In modeling the vacuum frying process, the following assumptions have been made.

2.2 General Assumptions

1. Heat is transferred from the oil to the product surface via convection and from the product surface internally via conduction.

2. Heat from the oil is used as sensible heat for increasing the water temperature to its boiling point, as heat of vaporization in the evaporation of liquid water to gaseous vapor, and as sensible heat in increasing the product

temperature toward the oil temperature.

3. The latent heat of vaporization cools the product region during evaporation, keeping the product temperature near the boiling point (until most of the water has been removed).

4. The drying rate is divided into a constant rate period and a falling rate period. Each period is characterized by an averaged set of heat and mass transport parameters.

5. During the constant drying rate, free water is removed as vapor via evaporation and diffusion from the product. The formation of the crust region is also taking place during this period.

6. During the falling rate region, a distinct crust region has been developed and bound water is being removed via vapor diffusion.

7. The rate of oil absorption is proportional to the rate of moisture loss during the constant rate period, but is limited by the presence of the crust during the falling rate period.

2.3 Heat and Mass Transfer Equations

The simplified heat transfer equation is given by Equation (1), which is a parabolic type equation consisting of the heat accumulation term, the conduction term, the heat source term ($Q_{heat\ source}$) denoting the latent heat of vaporization, and the convection term at the boundary surface, respectively:

$$\rho C_p \frac{dT}{dt} - div[k\nabla(T)] = Q_{heat\ source} + h(T_{oil} - T) \quad (1)$$

where,
ρ = density of product (kg/m^3)
C_p = heat capacity of product (J/kg C)
k = thermal conductivity (W/m C)
$Q_{heat\ source}$ = latent heat of evaporation term (J)
h = heat transfer coefficient (W/m^2 ^{o}C)
T_{oil} = oil temperature (^{o}C)
T = product temperature (^{o}C)

Equation (2) below represents the diffusion equation where the volume source term accounts for the convective flow of liquid and vapor. This equation is used to model the removal of free water and the absorption of oil in separate cases.

$$\frac{dc}{dt} - div(D \cdot \nabla(c)) = Q_{volume\ source} \quad (2)$$

where,
$\frac{dc}{dt}$ = change in concentration (kg mol/m^2 s)
D = diffusion coefficient (m^2/s)
c = concentration (kg mol/m^3)

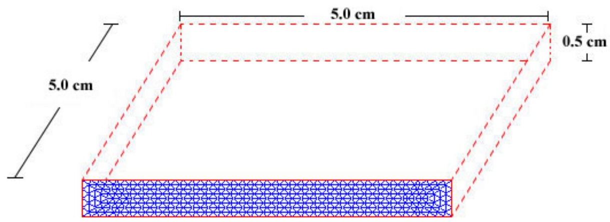

Figure 1. Cross-section view of a potato slice (5.0 cm x 5.0 cm x 0.5 cm) showing mesh refinement into 704 triangular elements and 401 nodes.

$Q_{volume\ source}$ = rate of convective flow of liquid (kg mol/m^2 s)

2.4 Two-Dimensional Model

Equations (1) and (2) were solved using the Finite Element toolbox in MATLAB 6.1 for potato slices of dimensions 5.0 cm x 5.0 cm x 0.5 cm. Since a 2-D model was investigated, the cross-section of the product was taken to represent the change in temperature, moisture content, and oil content inside the product. Figure 1 shows the cross-section of the potato slice that has been divided into 704 triangular elements and 401 nodes.

2.5 Input Parameters and Initial and Boundary Conditions

The transport parameters for the heat and mass transfer equations used in the simulation for both the constant drying rate period and the falling rate period are given in Table 1 (Rungsee, 2004). The frying temperature and pressure (120 C and 60 mm Hg) were chosen such that it corresponds to the optimum drying rate of the potato slices fried at ambient conditions of 165 C and 760 mm Hg (Yamsaengsung and Rungsee, 2003). The constant drying rate was determined to have taken place within the first 30 seconds of frying from a previous study (Yamsaengsung and Rungsee, 2003). After that, the parameters for the falling rate were used. The parameters were assumed to be constant during each of the drying periods.

The initial and boundary conditions are given in Table 2. The temperature at the surface of the product was taken to be the frying temperature of 120 C while the water and oil concentration at the surface (crust) were 0.08 kg mol/m^3 and 0.35 kg mol/m^3, respectively. These values were estimated from the experimental results (Rungsee, 2004) for the frying of potato slices at 120 C and 60 mm Hg.

3. Results and Discussions

3.1 Validation

The predicted models were compared to experimental data obtained by Rungsee (2004) for the frying of potato

Table 1. Parameters used in the transport equations for frying of potato slices at 120 C and 60 mm Hg.

	Properties	Values*
General Parameters	Density (*r*)	930 kg/m^3
	Heat Transfer Coefficient (*h*)	250 W/m^2 C
Heat Transfer Equation	Heat Capacity (C_p)	
	- Constant Period	3,450 J/kg C
	- Falling Period	3,050 J/kg C
	Thermal Conductivity (*k*)	
	- Constant Period	0.655 W/m C
	- Falling Period	0.495 W/m C
	Heat Source - Latent Heat of Vaporization ($Q_{heat\ source}$)	
	- Constant Period	32,000 J
	- Falling Period	17,000 J
Mass Transfer Equation	Effective Diffusivity of Water (D_{water})	
	- Constant Period	7.5 x 10^{-9} m^2/s
	- Falling Period	3.8 x 10^{-8} m^2/s
	Effective Diffusivity of Oil (D_{oil})	
	- Constant Period	6.1 x 10^{-9} m^2/s
	- Falling Period	1.4 x 10^{-8} m^2/s
	Volume Source - Convective Flow of Liquid and Vapor ($Q_{volume\ source}$)	
	- Constant Period	0.05 kg mol/m^2 s
	- Falling Period	0.05 kg mol/m^2 s

***From Rungsee (2004)**

Table 2. Initial and boundary conditions used for the frying of potato slices at 120 C and 60 mm Hg.

Initial Conditions		Boundary Conditions	
Parameter	**Value**	**Parameter**	**Values**
$T_{product}$	25 C	$T_{surface}$	120 C
c_{water}	0.90 kg mol/m^3	$c_{water,\ surface}$	0.08 kg mol/m^3
c_{oil}	0.00 kg mol/m^3	$c_{oil,\ surface}$	0.35 kg mol/m^3

slices under atmospheric and vacuum conditions. The vacuum condition was 120 C and 60 mm Hg. Results for the temperature profile, the drying curve and the oil absorption curve are shown in Figures 2 through 4. In Figure 2, the predicted model resulted in a slightly faster increase in temperature toward the boiling point of water both at the surface and at the center. The deviation could have resulted from the estimated parameters used in the model which does not account for structural changes such as expansion and puffing of the product. Still, the model shows the convergence of the surface temperature toward the frying temperature and a steady increase in the center temperature toward the frying temperature as the product reached very low moisture content.

In Figure 3, the predicted and experimental values are quite comparable, with the predicted model showing a faster decrease in moisture content at the 240 seconds mark. Again, a constant diffusivity value for water was used rather

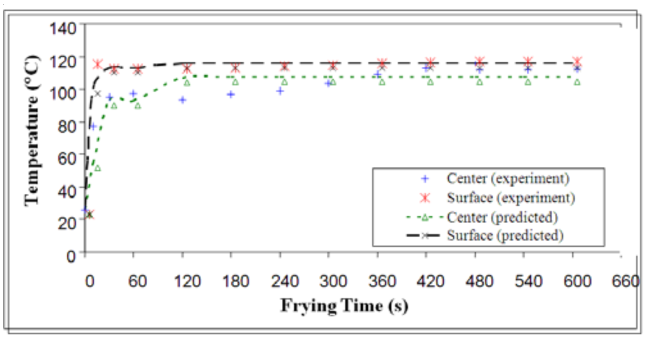

Figure 2. Experimental and predicted values for the temperature profiles of potato slices (5.0 cm x 5.0 cm x 0.5 cm) fried at 120 C and 60 mm Hg.

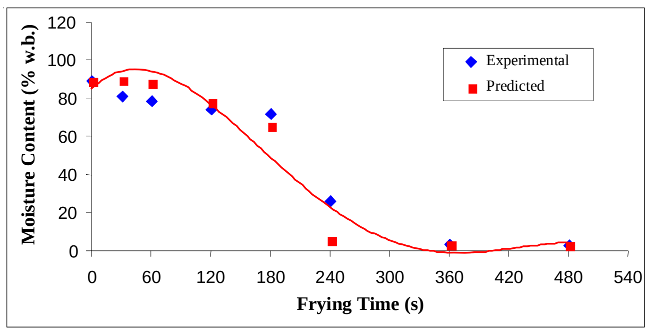

Figure 3. Experimental and predicted values for the moisture profiles of potato slices (5.0 cm x 5.0 cm x 0.5 cm) fried at 120 C and 60 mm Hg.

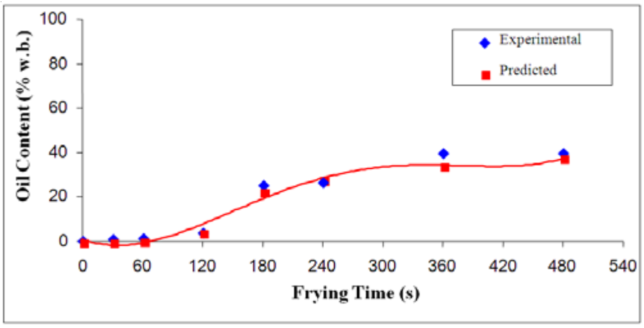

Figure 4. Experimental and predicted values for the oil absorption of potato slices (5.0 cm x 5.0 cm x 0.5 cm) fried at 120 C and 60 mm Hg.

than a more accurate formulation which changes with time. Finally, Figure 4 depicts a very agreeable result between the predicted and experimental model for oil absorption showing a rapid increase in oil absorption during the first 300 seconds of frying. These results altogether help to confirm the validity of the parameters chosen and the boundary conditions used.

3.2 Two-Dimensional Profiles

Figure 5 illustrates a picture of the 2-D temperature profile plotted against temperature, while Figures 6 and 7 depict the 2-D plot of the moisture profile and oil absorption profile. These results were obtained for vacuum frying at 120 C and 60 mm Hg. In the first figure, after 5 seconds of frying, there is a rapid increase in the temperature along the edge of the product, while the temperature along the middle of the product remains below 40 C. After 10 seconds, the gradient decreases rapidly with the center temperature rising above 60 C. After 30 seconds, the model predicted an average temperature above 100 C and moving rapidly toward the oil temperature of 120 C. This is due to the falling rate period that was assigned after the first 30 seconds, which involved a reduction in the latent heat of vaporization term allowing for a more rapid increase in temperature.

In order to understand the phenomena of crust formation and moving boundary better, the reader is referred to Figure 6. A crust region forms almost immediately (MC less than 10% w.b.) after just 5 seconds of frying, while the central portion of the potato slice remained at approximately 90% w.b moisture content. After 30 seconds of frying, a distinct crust layer has been formed, and the product enters the falling rate period. During this period, there is still a considerable amount of water within the center of the product. Even though the predicted average moisture content of the product agrees well with the experimental data from Figure 3, the result disagrees with the corresponding temperature profile, since at 60 seconds, the center temperature was predicted to be already above 100 C. Because the program uses 2 constant values for the latent heat of vaporization term, the model could have underestimated the

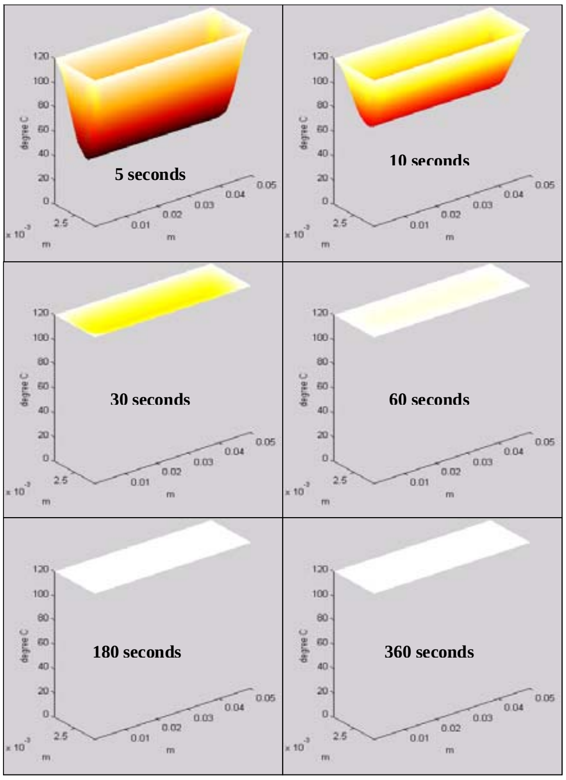

Figure 5. Three-dimensional plot of the temperature profile for potato slices at 5, 10, 30, 60, 180, and 360 s of frying. Fried at 120 C and 60 mm Hg; IMC, 90% w.b.; width, 5.0 cm; thickness 0.5 cm.

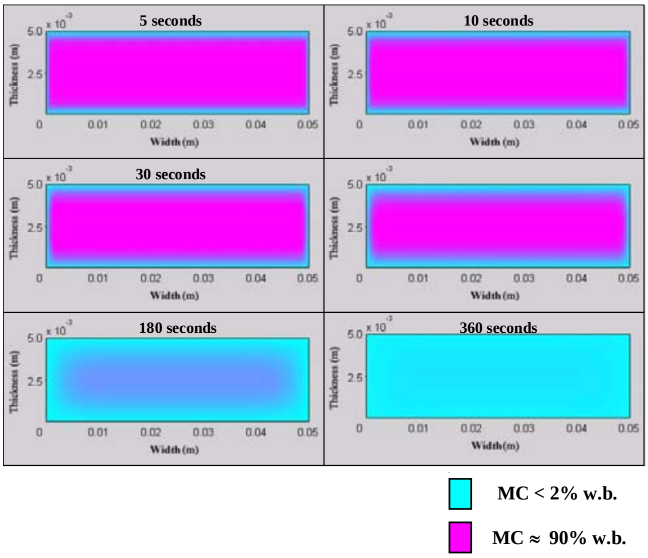

Figure 6. Two-dimensional plot of the moisture profile for potato slices at 5, 10, 30, 60, 180, and 360 s of frying. Fried at 120 C and 60 mm Hg; IMC, 90% w.b.; width, 5.0 cm; thickness 0.5 cm.

amount of heat removed during the initial stages of the falling period. As a result, the predicted temperature of the product was substantially higher than that of the experimental results shown in Figure 2. Nonetheless, after 180 seconds of frying,

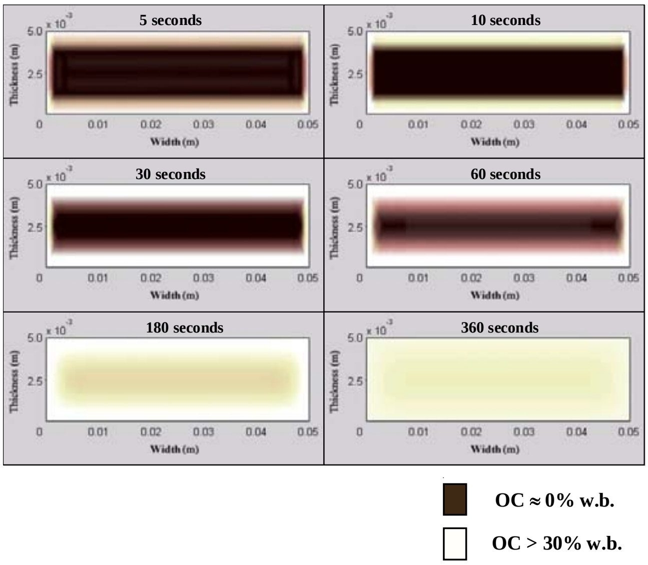

Figure 7. Two-dimensional plot of oil absorption for potato slices at 5, 10, 30, 60, 180, and 360 s of frying. Fried at 120C and 60 mm Hg; IMC, 90% w.b.; width, 5.0 cm; thickness 0.5 cm.

nearly one-third of the product can be considered crust, and finally, after 360 seconds, the entire product has a moisture content of less than 2% w.b. Hence the 2-D model is able to present a transient change in the thickness of the crust and its steady movement toward the center of the product.

Now, comparing the amount of oil absorption in Figure 7 to the amount of water removed in Figure 6, it can be seen that there is a rapid influx of oil during the first 5 seconds corresponding the removal of free water along the edge of the product. From 10 to 60 seconds of frying, there is a gradual absorption of oil along the surface and continual capillary diffusion of oil toward the center of the product, with the highest concentration scattered along the surface. Finally, if there is neither internal nor external force available to drive out the oil, the concentration of the oil will eventually equilibrate as oil continues to diffuse into the product. In reality, the fried products would have been removed after about 160-200 seconds of frying. This results in a higher concentration of oil along the surface (Yamsaengsung and Moreira, 2002b) than at the center. Furthermore, it should be noticed that there is no increase in the oil concentration at the surface after about 30 seconds of frying. After the initial influx, the formation of the crust helps to minimize more oil being absorbed into the product. The dispersion of the oil inside the product comes from the oil that had already entered the surface. Therefore, even though the oil concentration at the surface may already be above 30% after only 180 seconds of frying, the overall oil content of the product at this point is only 25% (See Figure 4).

From the results above, in order to reduce the amount of oil absorption into the product, the formation of the crust must take place. By looking at a combination of the temperature profile, the moisture profile, and the oil absorption profile, an optimum frying time can be deduced. In this case, the product becomes essentially dry (less than 2% M.C w.b.) after about 300 seconds of frying. A thinner product could be fried much faster and with the rapid formation of the crust, the amount of oil absorbed could be reduced. Still, the product cannot be too thin because it would have too much surface area for the oil to enter when water is being removed. Hence, the proper thickness and processing condition must be determined which would allow for rapid crust formation while minimizing the amount of oil absorbed into the product.

4. Conclusions

The Finite Element toolbox in MATAB 6.1 was used to model the changes in temperature, moisture content, and oil content during the vacuum frying of potato chips. Using the heat source term to represent the latent heat of vaporization term, the temperature profile at the center and at the surface can be predicted. By dividing the frying rate into 2 periods and using different sets of parameters, a moisture profile can be modeled to predict the initial constant rate period followed by the falling rate period. The following conclusions were made in this study:

1. The temperature of the product increases rapidly toward the boiling point of water at the associated pressure followed by the temperature's steady increase toward the frying oil temperature once the region becomes a crust.
2. The model predicted a rapid moisture loss of the product initially followed by a slow rate of moisture change. It also demonstrated the formation of the crust and the gradual increase in the crust thickness.
3. Finally, using two sets of diffusion coefficients that correlate to the two schemes of moisture loss, the model predicted the rapid flux of oil into the product during the constant drying stage, followed by gradual diffusion of oil into its interior once the crust had been established.

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