Low-Fat Fried Foods with Edible Coatings: Modeling and Simulation

R. Williams and G.S. Mittal

ABSTRACT

We studied the use of edible films to reduce fat absorption in fried foods. A mathematical model was developed incorporating heat, moisture and fat transfer in the food and the film. Moisture diffusivities of the food and the film were 0.33×10^{-7} m^2/s and 0.25×10^{-7} m^2/s, respectively. Fat diffusivities were 0.103×10^{-8} m^2/s for the food and 0.604×10^{-9} m^2/s for the film. Thermal diffusivities were 0.102×10^{-6} m^2/s for the food and 0.156×10^{-6} m^2 /s for the film. Film diffusivities were determined for gellan gum films at a thickness of 2.0 mm during frying.

Key words: modeling, simulation, frying, edible film, reduced fat

INTRODUCTION

IN DEEP-FAT FRYING OIL/FAT WHICH SERVES AS THE HEAT TRANSFER medium migrates into the food providing flavor and increasing caloric content (Gamble et al., 1987). Several studies reported that many hydrocolloids, long-chain polymers, especially cellulose derivatives, form gels which can be used in frying to reduce oil absorption (Sanderson, 1981; Dziezak, 1991; Mallikarjunan et al. 1995). Donhowe and Fennema (1994) reported that hydrocolloid based edible films could reduce oil migration during frying.

Models for frying and mass transfer in foods coated with edible films have been reported. A model for deep-fat frying of beef meatballs included heat, moisture and fat transfer represented frying of foods with high initial fat content (Ateba and Mittal, 1994) . Fat absorption and fat desorption (fat melts and starts to migrate out) periods were considered. The model used general diffusion equations for heat and moisture transfer and for fat transfer in the absorption period, and the capillary flow equation for fat transfer in the desorption period. Moreira et al. (1995a,b) used diffusion equations for moisture and heat transfer for oil uptake, moisture loss and temperature increase during frying of tortilla chips. For fat transfer into the chip they assumed that the oil accumulated on the surface and entered during cool down. Farkas et al. (1996a,b) modeled heat and moisture transfer during deep-fat frying using an infinite slab geometry and a moving boundary for the crust. The model did not include fat transfer.

Rumsey and Krochta (1994) studied various types of films and their uses, and modeled moisture transfer in a food coated with an edible film applying Fick's second law for transfer within the food and the film. Although the model was for food coated with an edible film, it did not include any heat or fat transfer. Heat and mass transfer were modeled during frying of edible film coated food considering film in the surface properties of the product (Mallikarjunan et al., 1995). These models for simultaneous heat, moisture and fat transfer in fried foods did not consider an edible film coating.

Our objective was to model the frying of edible film coated food considering heat, moisture and fat transfer in both the food and the film. The model was then applied to optimize the transport properties of the film to minimize fat penetration into the fried food.

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MODEL DEVELOPMENT

THE MODEL WE DEVELOPED WAS SIMILAR TO THAT OF ATEBA AND Mittal (1994), the differences being the addition of edible film and use of a low fat product (where fat transfer mechanism is by diffusion only) rather than a high fat product. During frying, heat is transferred to the surface of the food by convection from the frying oil, and through the product by conduction. Moisture from the food migrates out of the food due to a concentration gradient and, similarly, fat from the frying medium is transferred into the product. The differential equations for energy, moisture and fat transfer in both the food and the film coating were modeled using Fourier's and Fick's laws, and solved numerically by finite differences. Heat and mass transfer were considered to be coupled only at the surface where heat transfer was most affected by evaporative cooling.

A disc geometry was considered with diameter to half thickness ratio of 9, thus heat transfer was considered one-dimensional in the axial direction. As the product was symmetrical about the center-line, the model described the product from the product center to its outer layer. There were 11 nodal elements considered, 1 to 7 in the food, 8 at the interface of the food and the film, and nodes 9, 10 and 11 were in the film. The instantaneous values of moisture, fat and temperatures at the center of the nodes were considered representative of the entire node. The following assumptions were made:

(1) The food was homogeneous and isotropic.

(2) Shrinkage and crust formation were negligible.

(3) Thermal, moisture and fat diffusivity values of the food and the film were constant and different.

(4) Initial moisture and fat contents of the food and the film were constant and different.

(5) Initial moisture content at the interface of the food and the film was equal to the average of the two initial moisture contents, and likewise for fat content at the interface.

(6) The surface moisture and fat contents of the product reached equilibrium with the surroundings instantaneously.

(7) The heat transfer due to migration of water and fat from one node to another node was neglected because (i) heat transfer by conduction was the major mode of heat transfer within the product, and (ii) a relatively small amount of water and fat was transferred per unit time from one node to another.

(8) The evaporation of water was also considered to take place only at the surface of the product, because crust thickness was negligible.

A cross section of the coated food with a total thickness of 2L is shown (Fig. 1) which indicates the location of the nodes in the product. The differential equations are as follows:

Moisture, fat, and heat transfer:

$$\frac{\delta m}{\delta t} = D_m \frac{\delta^2 m}{\delta x^2}; \quad \frac{\delta mf}{\delta t} = D_{mf} \frac{\delta^2 mf}{\delta x^2}; \quad \frac{\delta T}{\delta t} = \alpha \frac{\delta^2 T}{\delta x^2} \qquad (1)$$

Fick's and Fourier's laws were used for internal nodes, while heat and mass balances were used for nodes in the film and interfaces.

Initial conditions: Initial temperature constant: T(x,0) = To. Initial moisture and fat contents constant but different in the food and film.

At the interface, the moisture and fat contents were a function of the fat.

$$m(x < L - th) = m_{01};\ m(x > L - th) = m_{02}$$
$$m(x = L - th) = (m_{01} + m_{02})/2 \qquad (2)$$

$$mf\,(x < L - th) = mf_{01};\ mf\,(x > L - th) = mf_{02}$$
$$mf\,(x = L - th) = (mf_{01} + mf_{02})/2 \qquad (3)$$

Boundary conditions: No temperature, moisture or fat gradients exist at the center of the product. Thus:

$$\frac{\delta T}{\delta x}(x=0) = 0; \quad \frac{\delta m}{\delta x}(x=0) = 0; \quad \frac{\delta mf}{\delta x}(x=0) = 0 \qquad (4)$$

At the outside film surface, convective heat transfer from the oil equals conduction to the center of the product plus latent heat of moisture evaporation:

$$h(T_a - T_s) = k_2 \frac{\delta t}{\delta x}\Big|_{x=L} + D_{m2}\rho_2 L_v \frac{\delta m}{\delta x}\Big|_{x=L} \qquad (5)$$

Since surface moisture and fat contents attain equilibrium with surroundings instantaneously:

$$m_s\,(t>0) = m_e;\ mf_s\,(t>0) = mf_e \qquad (6)$$

Converting variables to dimensionless terms:

$$\theta = \frac{T - T_0}{T_a - T_0}; \quad C = \frac{m - m_e}{m_{01} - m_e}; \quad Cf = \frac{mf - mf_e}{mf_{01} - mf_e} \quad \psi = \frac{x}{L} \qquad (7)$$

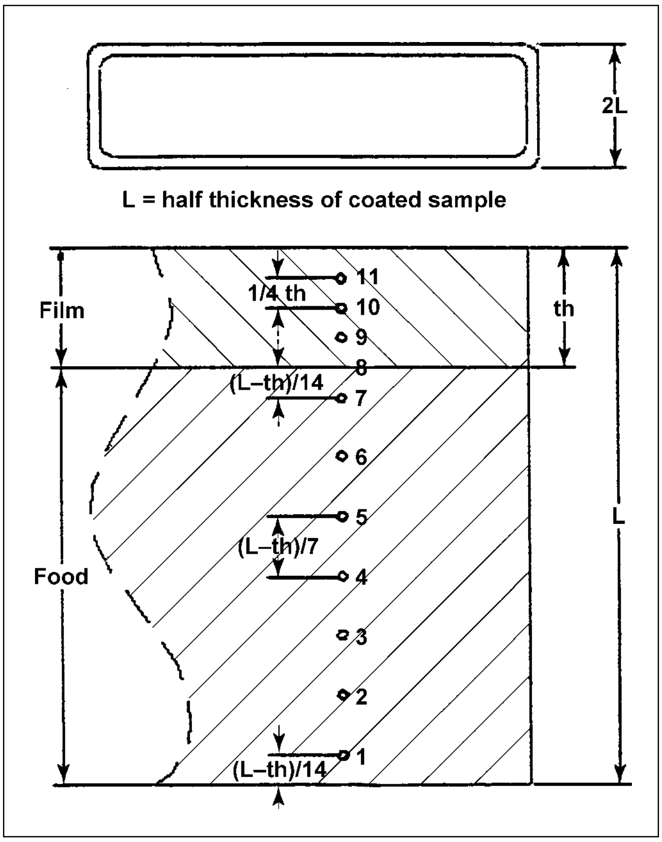

Fig. 1—Placement of nodes used in the model.

$$\frac{\delta\theta}{\delta t} = \frac{\alpha}{L^2}\frac{\delta^2\theta}{\delta\psi^2}; \quad \frac{\delta C}{\delta t} = \frac{D_m}{L^2}\frac{\delta^2 C}{\delta\psi^2}; \quad \frac{\delta Cf}{\delta t} = \frac{D_{mf}}{L^2}\frac{\delta^2 C_f}{\delta\psi^2} \qquad (8)$$

The dimensionless initial and boundary conditions become:

$$\theta(\psi,0) = 0 \qquad (9)$$

$$C\left(\psi < \frac{L-th}{L}\right) = C_{01} = 1; \quad C\left(\psi > \frac{L-th}{L}\right) = C_{02} = \frac{m_{02} - m_e}{m_{01} - m_e}$$

$$C\left(\psi = \frac{L-th}{L}\right) = \frac{C_{01} + C_{02}}{2}: \quad Cf\left(\psi = \frac{L-th}{L}\right) = \frac{Cf_{01} + Cf_{02}}{2} \qquad (10)$$

$$Cf\left(\psi < \frac{L-th}{L}\right) = Cf_{01} = 1; \ Cf\left(\psi > \frac{L-th}{L}\right) = Cf_{02} = \frac{mf_{02} - mf_e}{mf_{01} - mf_e} \qquad (11)$$

$$\frac{\delta\theta}{d\psi}(\psi=0) = 0; \quad \frac{\delta C}{d\psi}(\psi=0) = 0; \quad \frac{\delta Cf}{d\psi}(\psi=0) = 0 \qquad (12)$$

$$h(T_a - T_s) = k_2 \frac{(T_a - T_0)}{L}\frac{\delta\theta}{\delta\psi}\Big|_{\psi=1} + D_{m2}\rho_2 L_v \frac{(m_0 - m_e)}{L}\frac{\delta C}{\delta\psi}\Big|_{\psi=1} \qquad (13)$$

$$C_s\,(t>0) = C_e = 0; \quad Cf_s\,(t>0) = Cf_e = 0 \qquad (14)$$

Nodal equations: The space variable was eliminated in the dimensionless equations, and the finite difference equations for each of the 11 nodes and the surface are as follows:

Node 1:

$$\frac{d\theta_1}{dt} = \frac{196\alpha_1}{3(L-th)^2}(\theta_2 - \theta_1); \quad \frac{dC_1}{dt} = \frac{196D_{m1}}{3(L-th)^2}(C_2 - C_1)$$
$$\frac{dCf_1}{dt} = \frac{196D_{mf1}}{3(L-th)^2}(Cf_2 - Cf_1) \qquad (15)$$

Nodes 2 to 6:

$$\frac{d\theta_1}{dt} = \frac{49\alpha_1}{L-th)^2}(\theta_{i+1} - \theta_1 + \theta_{i-1}); \quad \frac{dC_1}{dt} = \frac{49D_{ml}}{(L-th)^2}(C_{i+1} - 2C_i + C_{i-1})$$
$$\frac{dCf_1}{dt} = \frac{196D_{mf1}}{3(L-th)^2}(Cf_2 - Cf_1) \qquad (16)$$

Node 7:

$$\frac{d\theta_7}{dt} = \frac{196\alpha_1}{3(L-th)^2}(2\theta_8 - 3\theta_7 + \theta_6); \quad \frac{dC_7}{dt} = \frac{196D_{m1}}{3(L-th)^2}(2C_8 - 3C_7 + C_6)$$
$$\frac{dCf_7}{dt} = \frac{196D_{mf1}}{3(L-th)2}(2Cf_8 - 3Cf_7 + Cf_6) \qquad (17)$$

Node 8:

$$\frac{d\theta_8}{dt} = \frac{1}{\frac{th.k_2}{8\alpha_2} + \frac{(L-th)k_1}{28\alpha_1}} \left[\frac{4k_2}{th}(\theta_9-\theta_8) - \frac{14k_1}{(L-th)}(\theta_8-\theta_7)\right] \quad (18)$$

$$\frac{dC_8}{dt} = \frac{1}{\frac{L-th}{28} + \frac{th}{8}} \left[\frac{14D_{ml}}{L-th}(C_7-C_8) - \frac{4D_{m2}}{th}(C_8-C_9)\right] \quad (19)$$

$$\frac{dCf_8}{dt} = \frac{1}{\frac{L-th}{28} + \frac{th}{8}} \left[\frac{14D_{mfl}}{L-th}(Cf_7-Cf_8) - \frac{4D_{mf2}}{th}(Cf_8-Cf_9)\right]$$

Node 9:

$$\frac{d\theta_9}{dt} = \frac{16\alpha_2}{th^2}(\theta_{10}-2\theta_9+\theta_8); \quad \frac{dC_9}{dt} = \frac{16D_{m2}}{th^2}(C_{10}-2C_9+C_8) \quad (20)$$

$$\frac{dCf_9}{dt} = \frac{16D_{mf2}}{th^2}(Cf_{10}-2Cf_9+Cf_8)$$

Node 10:

$$\frac{d\theta_{10}}{dt} = \frac{16\alpha_2}{th^2}(\theta_{11}-2\theta_{10}+\theta_9); \quad \frac{dC_{10}}{dt} = \frac{16D_{m2}}{th^2}(C_{11}-2C_{10}+C_9)$$

$$\frac{dCf_{10}}{dt} = \frac{16D_{mf2}}{th^2}(Cf_{11}-2Cf_{10}+Cf_9) \quad (21)$$

Node 11:

$$\frac{d\theta_{11}}{dt} = \frac{16\alpha_2}{th^2}(\theta_s-2\theta_{11}+\theta_{10}); \quad \frac{dC_{11}}{dt} = \frac{16D_{m2}}{th^2}(C_s-2C_{11}+C_{10}) \quad (22)$$

$$\frac{dCf_{11}}{dt} = \frac{16D_{mf2}}{th^2}(Cf_s-2Cf_{11}+Cf_{10})$$

Surface:

$$\theta_s = \frac{h.th + 4k_2\theta_{11} + 4D_{m2}\rho_2 L_v \frac{(m_{01}-M_e)}{(T_a-T_0)}(C_s-C_{11})}{h.th+4k_2} \quad (23)$$

Average values: The average values for temperature, moisture and fat, used to compare the experimental values, were calculated using the following equation:

$$m_{avg} = \frac{\sum_{i=1}^{11} v_i m_i}{v_{total}} \quad (24)$$

Table 1—Thermo-physical property values

Property	Source	Value
Heat transfer coefficient	Miller et al. (1994)	246 W/(m²·K)
Food density	measured (dry mass/volume)	835.96 kg/m³
Film density	measured (dry mass/volume)	13.26 kg/m³
Interfacial density	calculated from measured food and film dry densities	295.5 kg/m³
Density of food nodes	calculated from measured food and film dry densities	707.1 kg/m³
Total density	calculated from measured food and film dry densities	487.8 kg/m³
Food thermal conductivity	Choi and Okos (1986)	0.351 W/(m.K) at 373 K
Film thermal conductivity	Choi and Okos (I 986)	0.607 W/(m.K) at 373 K
Latent heat of vaporization	Incropera and De Witt (1990)	2257 kJ/kg at 373 K

The equation for moisture is given below, similar equations were obtained for temperature and fat by replacing "m" with "T" or "mf".

$$m_{avg} = \frac{L-th}{7L}(m_1+m_2+m_3+m_4+m_5+m_6) + \frac{3L-3th}{28L}m_7 + \left(\frac{L-th}{28L} + \frac{th}{8L}\right)m_8 + \frac{th}{4L}(m_9+m_{10}) + \frac{3th}{8L}m_{11} \quad (25)$$

Weighted moisture and fat contents: The dry basis densities of the food and the film were very different and this biased the results. Thus, weighted moisture and fat contents based on density were used in the model at the interface to avoid instability in the numerical solution. The gellan gum film had a very high moisture content (98.6%wb or 67.6%db) and a very low dry density as compared to the food (836 kg/m^3 for the food and 13.3 kg/m^3 for the film). To eliminate differences in dry densities of the food and film, the initial moisture and fat contents were weighted based on dry densities:

$$m_{01}(\text{weighted}) = m_{01}\frac{\rho_1}{\rho_{total}}; \quad m_{02}(\text{weighted}) = m_{02}\frac{\rho_2}{\rho_{total}} \quad (26)$$

Similar equations were developed for fat.

Simulation

Models for moisture, fat and heat transfer were simulated using ISIM simulation software (Dunn et al., 1992). The heat transfer coefficient at the frying medium interface was 246.5 W/(m^2.K) (Miller et al., 1994). Thermal conductivities of the food and the film were calculated using a formula developed by Choi and Okos (1986), based on temperature and the compositions. The thermal, moisture and fat diffusivity values of the food and the film (Table 1) were calculated from experimental data using an iterative process by minimizing the root mean square of the deviations between simulated and experimental results as follows:

$$rms = \sqrt{\sum_0^t \frac{(X_{predicted} - X_{experimental})^2}{t}} \quad (27)$$

Diffusivity values in the food were determined from results of non-coated samples and a modified model for non-coated food. The diffusivity values of non-coated food were then used in the model for frying coated food to determine film properties. One set of experimental data was used to determine transport properties and another set was used to validate the model. The rms was minimized using an optimization program developed by Hooke and Jeeves (1961).

MATERIALS & METHODS

Edible films

Gellan gum was Kelcogel F (Kelco, 1995), a polysaccharide produced by *Pseudomanas elodea*. Gellan gum films are strong, brittle and provide good oil barrier properties. Gellan coated products resulted in 35% to 63% oil absorption reduction relative to non-coated products (Kelco, 1995). Film application method was important because it affects film thickness, texture, evenness and ease of application. The food samples were dipped in gellan gum solution for 10 s and air dried. Coated and non-coated samples were weighed, and the disc thickness was measured before and after coating to verify that the density and film thickness were the same on all samples. Samples coated with 2.0–2.5 mm thick gellan gum film were used for model validation experiments.

Table 2—Average moisture and fat content of fried samples. Shape: discs with 4.5 cm diameter and 0.8 cm thickness; film thickness: 2.0–2.5 mm

Coating	None	Gellan gum	None	Gellan gum
Frying time	Moisture content (%db)	Moisture content (%db)	Fat content (%db)	Fat content (%db)
0 min	51.76/0.36 b	105.82/3.04 a	14.16/0.09 bbb	15.31/0.99 aaa
1 min	35.88/1.70 bb	79.04/6.00 aa	18.53/0.53 AAA	16.05/1.60 BBB
3 min	21.54/2.12 B	50.67/4.44 A	21.68/2.05 a’	18.74/1.54 b’
4 min	17.38/2.53 BB	49.10/3.45 AA	25.47/ 1.83 a”	18.51/1.30 b”

Note: Means with different letters are significantly different at the 95% level; a,b=results of Duncan’s comparison for moisture content after 0 min of frying;; aa,bb=results of Duncan’s comparison for moisture content after 1 min of frying; A,B=results of Duncan’s comparison for moisture content after 3 min of frying; AA,BB=results of Duncan’s comparison for moisture content after 4 min of frying; aaa,bbb=results of Duncan’s comparison for fat content after 0 min of frying; AAA,BBB=results of Duncan’s comparison for fat content after 1 min of frying; a’,b’=results of Duncan’s comparison for fat content after 3 min of frying; a”,b”=results of Duncan’s comparison for fat content after 4 min of frying; numbers after “/” are standard deviations.

Food product and frying medium

Several products were tested for ease of use, consistency and fat content. A low fat product which absorbed enough fat to permit comparison of the effects of coating on fat absorption was desired. Frozen potatoes, rehydrated potato starch, mashed potatoes, Russet Fries (Basic American Foods, Blackfoot, ID) and commercial pastry mixes were tried. The food selected for study was PC Uncommonly Light Biscuit Mix (President Choice, Toronto, Canada) rehydrated with water in a mass ratio of 2.45g pastry mix to 1g water. Discs of 4.5 cm dia and 0.9 to 1.0 cm thickness were formed using a cookie press (Progressive International Corp., Kent, WA). The dough was packed into the press, dispensed and cut to the desired thickness.

The discs were fried in Frilite pourable frying shortening (CanAmera Foods, Toronto, Ontario). The frying oil contained hydrogenated soybean oil, 2 ppm dimethylpolysiloxane and 0.04% maximum free fatty acid, and peroxide value (P.V.) of 0.5 meq/kg maximum and smoke point of 491K minimum.

Fryer and temperature measurement

The fryer was a T-Fal Super-control home deep-fat fryer (SEB Canada Inc., Scarborough, Ontario) with electronic on-off temperature control and timer. Temperature fluctuated 10 to 20°C. At 160°C or 170°C set point, the average oil temperature was slightly higher than 150°C. At 180°C set point, oil temperature was 175°C. At 150°C set point, the average oil temperature was 150°C. Therefore, set point of 150°C was used. Frying oil temperature fluctuations were included in the computer program. A meshed screen held the samples completely immersed in the oil.

A LabMate Model 902 CPU and a Model 7000 Electronic Measurement and Control System (EMCS) (Sciemetric Instruments, Nepean, Ontario), and a laptop computer (Tandy 200, Radio Shack Inc., Barrie, Ontario) in either interactive or stand-alone mode were used. In the stand-alone mode, the CPU was controlled by a BASIC program which used several standard commands (Sciemetric Instruments Inc., 1987). Temperature was measured using copper-constantan thermocouples (Kapton Insulated Duowrap™ Parallel Duplex Thermocouple wire, Model k/k-16-xx, Thermo Electric Canada Ltd., Toronto, Ontario). To secure positioning of the thermocouple in the product center, a heat resistant plastic holder was designed and built. The holder held the food around the circumference and a small hole was drilled into holder top to held the thermocouple in the center. The food in the holder was dipped in the frying oil. Temperatures of samples with and without the holder were the same. The oil temperature was also continuously monitored in the tests.

Experimental procedure

Samples were prepared, weighed and thickness measured. Samples were coated and dried, then reweighed and thickness measured again. Samples were fried, then blotted with tissue paper to remove surface oil. Samples were then cooled and weighed. Moisture of the samples was determined using an air oven (Cole Parmer, Chicago, IL) at 130°C for 16h (#925.10, AOAC, 1990). Fat content was determined (on dried samples) using an 8h Soxhlet extraction method (#920.85, AOAC, 1990). Before frying, all samples were stored in Ziploc bags in the freezer and thawed at room temperature prior to use. Fried samples were immediately dried in the air oven, prepared for fat extraction and then stored in a dessicator until further use.

Two replications of three each of non-coated or coated samples were fried for 0, 1, 3 or 4 min. Frying was in random order and the oil was changed after 4 fryings. A fourth sample was fried in the plastic holder and with the other three, and was used to record temperature data.

Data analysis

The final moisture and fat contents of samples were analyzed using *SAS/ANOVA* (SAS Institute, Inc., 1993), and Duncan’s procedure was used to compare means at $p \leq 0.05$.

RESULTS & DISCUSSION

AVERAGE MOISTURE AND FAT CONTENTS OF FRIED SAMPLES WERE compared (Table 2). A difference was found ($p=0.05$) between coated and non-coated samples at any frying time. Moisture contents of coated samples were always higher than non-coated samples. The initial moisture contents of coated samples were also higher due to higher moisture content of the coating, therefore, the total moisture loss was higher in coated samples than in non-coated. The fat contents of coated samples were 8% higher initially and lowered by as much as 27% after 1, 3 and 4 min of frying than the fat contents of non-coated samples.

Fat transfer

Initially, coated samples had slightly higher fat contents than non-coated samples (Table 2), but, after 1, 3 and 4 min of frying, coated samples had lower fat than non-coated. Gellan gum films (thickness 2.0–2.5 mm) reduced the fat absorption by 60%. Fish pieces deep-fried for 2 min at 182°C showed that gellan gum films reduced fat absorption by as much as 63% (Kelco, 1995), depending on concentration of gellan gum solution applied.

Experimental and simulated fat content were compared vs frying time for non-coated and coated foods (Fig. 2). Fat diffusivity was 0.103×10^{-8} m^2/s and 0.604×10^{-9} m^2/s for the food and the film respectively. This compares with values of 0.287×10^{-7} m^2/s in frying of meatballs (Ateba and Mittal, 1994), 1.321×10^{-5} m^2/s in tortilla chips (Moreira et al., 1992) and 4.9 to 12.2×10^{-8} m^2/s in restructured potato product (Rubnov and Saguy, 1996). The diffusivities we determined were different due to the use of a different product. Fat diffusivity in the film was about half the value in the food. Thus the film acted as a barrier to fat absorption. Plot of experimental and simulated fat contents vs time showed (Fig. 2) that the simulated results were in good agreement with the experimental (R^2 0.974).

Moisture transfer

Simulated and experimental moisture content were compared (Fig. 3) vs frying time for coated and non-coated samples. At all times, coated samples had higher moisture than non-coated samples. Total moisture loss from coated samples was higher than non-coated samples because the films had very high moisture (98%wb). Moisture diffusivity values were 0.33×10^{-7} m²/s and 0.25×10^{-7} m²/s respectively for food and film. This compares with moisture diffusivity of 8.897×10^{-6} m²/s in frying of tortilla chips at 180°C (Moreira et. al., 1992), 1.32×10^{-9} to 1.64×10^{-8} m²/s in chicken drum frying at 120-180°C (Ngadi and Correia, 1995), and 1.04×10^{-9} m²/s in dried gel and 1.08×10^{-13} m²/s in chocolate coating (Rumsey and Krochta, 1993). The moisture diffusivities we determined for the food and film were different due to the different food and film used.

Heat transfer

Simulated and experimental average temperatures were also compared (Fig. 4) vs frying time for coated and noncoated samples. Thermal diffusivity values for food and film were 1.02×10^{-7}m²/s and 1.56×10^{-7} m²/s respectively. Although thermal diffusivity for the film was slightly higher than for the food, the coated sample temperatures increased slower than noncoated samples because of evaporative cooling in coated samples, which lost more moisture. The temperature difference between coated and noncoated samples did not affect fat absorption. Fat content of coated samples after 4 min of frying (18.74%db) was less (Table 2) than in noncoated samples after 3 min of frying (21.68%db) when the samples were at almost the same temperature. Coated samples at the same temperature had lower fat contents than non-coated samples at the same temperature.

Other reported thermal diffusivity values during food frying are: 1.33×10^{-7} m²/s in frying of meatballs at 159°C (Ateba and Mittal, 1994) and 9.11×10^{-8} m²/s in frying of tortilla chips at 190°C (Moreira et al., 1995b). The thermal diffusivity we determined were within the range of reported thermal diffusivity values. The plot of simulated and experimental temperatures vs frying time and the high R^2 value (0.994) indicated that the model was effectively predicting the temperature history during frying of a coated food.

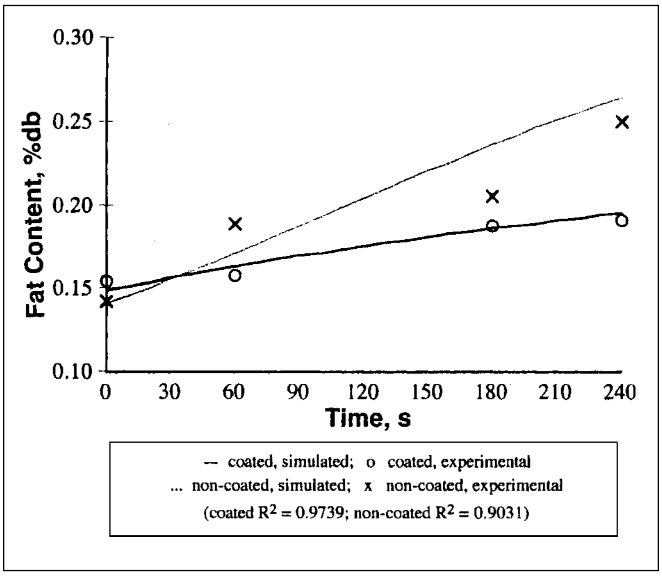

Fig. 2—Observed and predicted fat content.

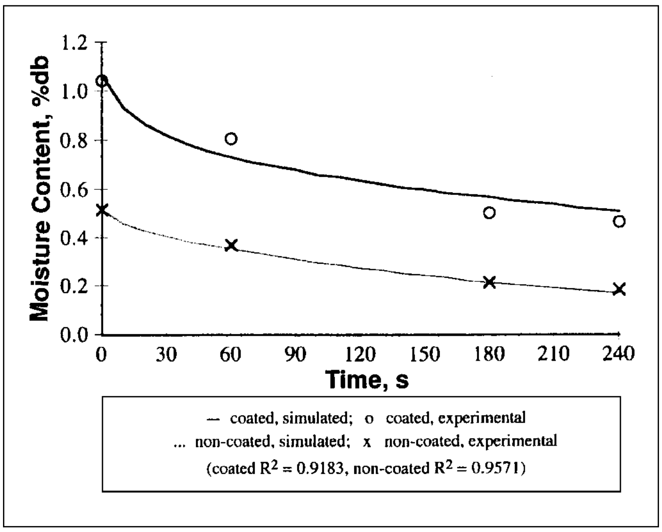

Fig. 3—Observed and predicted moisture content.

Optimization of film properties

The model can be used to optimize film properties or to predict results of using a particular film with a specific product under different frying conditions. The fat contents were plotted vs frying time (Fig. 5) of the same food, fried under the same conditions, with same film thickness but different fat diffusivity values. As film fat diffusivity decreased, fat transfer into the food also decreased. At 0.1×10^{-10} m²/s, there was a very small change in initial fat content of coated product. The model will indicate film fat diffusivity required to achieve desired fat content in a product. Conversely, if a specific film (with known diffusivity) has been chosen, the model can predict the fat content histories.

The model can also be used to optimize moisture transfer properties of the film. Moisture content was plotted vs frying time (Fig. 6) of a food fried with films of different moisture diffusivity values. As film moisture diffusivity decreased, moisture retention increased. At a film moisture diffusivity of 0.1×10^{-9} m²/s, initial product moisture content had not changed much. In the same way the model could be used to select a film for required moisture transfer during food frying.

The optimization of film properties with the model can be used to design new films. With application specific properties using composite films of two types of materials. Films from new materials would be difficult to design as the factors affecting diffusivity would not be known. Composite films, on the other hand, may be feasible as two or more film materials with different known diffusivity values could be combined to form films with desired properties. The model therefore could be impor-

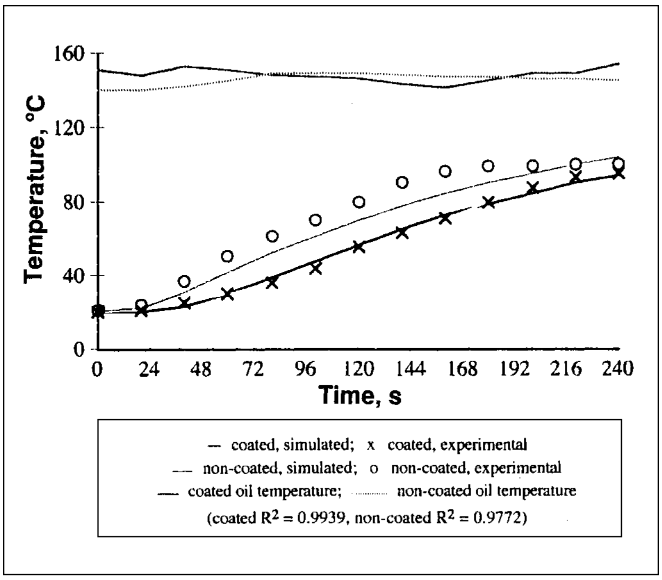

Fig. 4—Observed and predicted temperature at the geometric center of the food.

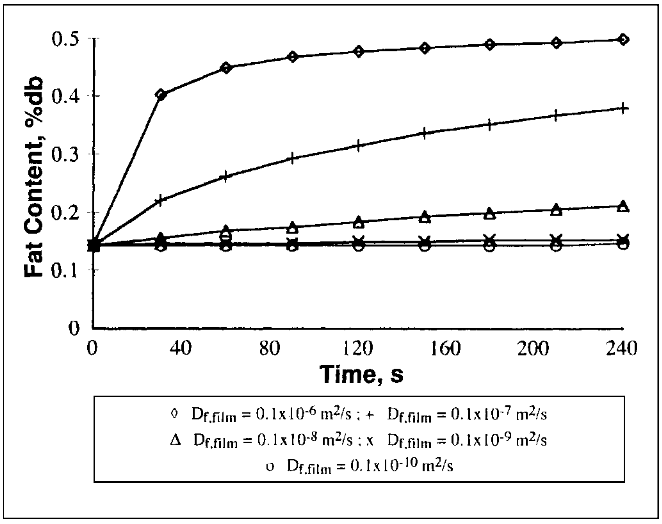

Fig. 5—Effect of film fat diffusivity on fat content during deep-fat frying.

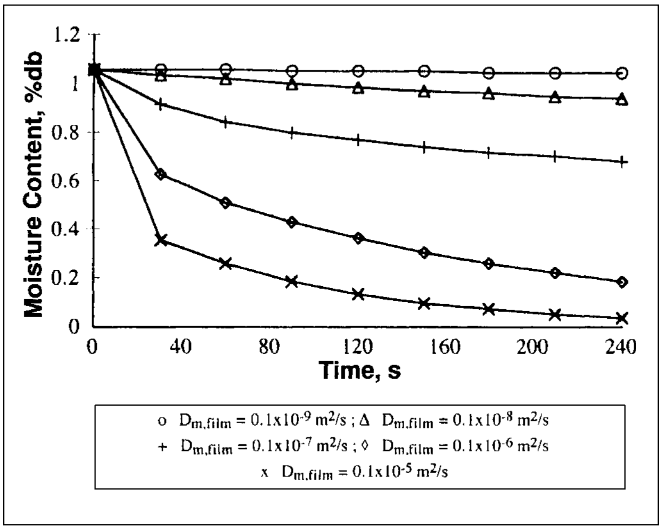

Fig. 6—Effect of film moisture diffusivity on moisture content during deep-fat frying.

tant when using edible film coatings to manufacture low fat foods.

CONCLUSIONS

A MATHEMATICAL MODEL WAS DEVELOPED TO DESCRIBE MOISTURE, fat and heat transfer mechanisms that take place during deep-fat frying of foods coated with an edible film. Experimental results were found to validate this model. The model for fat transfer was in good agreement with experimental results, (R^2 0.974). The fat diffusivity of gellan gum film (thickness 2.0 mm) was 0.604×10^{-9} m²/s, half that of the food (0.103×10^{-8} m²/s). The model for moisture transfer resulted in R^2 0.918, between predicted and experimental results. The moisture diffusivity of gellan gum film (thickness 2.0 mm) and the moisture diffusivity of the food were 0.25×10^{-7} m²/s and 0.33×10^{-7} m²/s, respectively. The heat transfer model was in good agreement with experimental results (R^2 0.994). The thermal diffusivity of gellan gum film (thickness 2.0 mm) and the thermal diffusivity of the food were 0.156×10^{-6} m²/s and 0.102×10^{-6} m²/s , respectively.

LIST OF SYMBOLS

C	dimensionless moisture content
Cf	dimensionless fat content
D_m	moisture diffusivity, m²/s
D_{mf}	fat diffusivity, m²/s
h	heat transfer cofficient, W/(m²·K)
k	thermal conductivity, W/(m·K)
L	half thickness of the food slab, m
L_v	latent heat of vaporization, J/kg
m	moisture content, dry basis
mf	fat content, dry basis
rms	root mean square of deviations
T	temperature, K
t	time, s
th	film thickness, m
v	value
X	fat content, moisture content or temperature in Eq (27)
x	distance from the center of the food, m
α	thermal diffusivity, m²/s
ρ	dry density, kg/m³
θ	dimensionless temperature
Ψ	dimensionless distance

Subscripts

avg	average
e	equilibrium
0	initial
a	ambient
s	surface
1	denotes food properties
2	denotes film properties
0-11	nodes

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