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Research Article

Finite Element Modeling of Potato Frying for Prediction of Temperature and Moisture Changes

Deniz Cekmecelioglu*, **Oya N. Uncu**

Department of Food Engineering, Middle East Technical University, Ankara, Turkey

***Corresponding author:** Deniz Cekmecelioglu, Department of Food Engineering, Middle East Technical University, 06800, Ankara, Turkey, Tel: +90 3122105631; Fax: +90 3122102767; E-mail: denizc@metu.edu.tr

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Abstract

Frying of potato slices was modeled using finite element method for real time control and better understanding of temperature and moisture developments. The model was validated by temperature values measured at the center and moisture content of whole slices sampled periodically during frying. The model results were acceptable for both temperature (R2=0.718-0.915) and moisture content (R2=0.753-0.910) predictions compared to experimental values resulted from frying at 150, 170 and 190°C in sunflower seed oil. The results indicated that the simplified finite element model with constant diffusivity can be used for successful estimates of temperature and moisture changes during potato frying.

Keywords: Acrylamide; Finite Element Method; Frying; Temperature; Moisture

Abbreviations

ρ	:	Density, Kg/M^3
C	:	Heat Capacity, J/Kgk
T	:	Temperature, °C
k	:	Thermal Conductivity, W/mK
c	:	Moisture Concentration, mol/m^3
D	:	Moisture Diffusivity, m^2/s
h	:	Heat Transfer Coefficient, W/m^{2}K
Text	:	oil temperature, °C
λ	:	Latent Heat of Vaporization, J/kg
kc	:	Mass Transfer Coefficient, m/s
Ts	:	surface temperature, °C
m	:	Moisture Content, g

Introduction

Frying is a thermal process, which involves immersion and cooking of food in hot oil and widely used in the food industry [1]. Heat is transferred from oil to the food surface by convection and from surface to inside the product by conduction [2]. Moisture is also evaporated from the product while oil is absorbed. Thus, there also exists a mass transfer accompanying the heat transfer during frying.

Heat and mass transfer problems can be solved by analytical and numerical methods. Analytical solutions are available only for simple geometries and for simple initial and boundary conditions. When the system properties become dependent on location or concentration, the solution starts to be more complicated and often may not exist if convection boundary conditions are included [3]. Among the numerical techniques available to solve such complex and real life cases are the Finite Difference (FDM) and the Finite Element Method (FEM). Solutions by FDM require long computational times and the material properties are difficult to vary from node to node [4]. However, FEM is a more powerful technique that solves problems with complex mixed boundary conditions, gives results of higher accuracy and is applicable to more random geometry cases than the FDM.

Current literature has intensive work on basic heat and mass transfer parameters during potato frying. A number of researchers determined the heat transfer coefficient for varying oil temperatures (140-190°C) and geometry of potato slices (strip, disc, etc.) [2,5,6]. Hubbard and Farkas [7] utilized the time-temperature data to determine the heat transfer coefficient during frying of infinite potato cylinders. Yildiz et al. [8] determined mass transfer coefficient from time-moisture data of potato slices fried at 150-190°C. However, the use of heat and mass transfer parameters in predicting the temperature and moisture profiles over varying frying conditions still needs to be widespread.

Temperature is one condition associated with acrylamide formation in frying process although different mechanisms are available in literature. As Zyzak et al. [9] reported that N-glycosides formed by reaction of reducing sugar with asparagine results in significant amounts of acrylamide on heating. Becalski et al. [10] reported that temperatures >100°C is required for acrylamide formation (as cited by Pedreschi et al. [11]. Tareke et al. [12] determined that acrylamide was formed above 120°C in potato chips. Due to the fact that acrylamide is not formed during boiling, higher temperatures and/or low moisture are needed for its formation [13]. It is also obvious that moisture distribution influences the temperature field by vaporization and by changes in thermal conductivity. Thus, temperature and moisture profiles are the major drivers of acrylamide formation and monitoring them is of beneficial task for quality of fried foods.

The main objective of this study is to model potato frying process by finite element method and to predict temperature and moisture profiles of potato slices, preferably in the centre location, making use of the inter-related heat and mass transfer equations. The modeling approach used in this study can contribute to optimization and real time process control of frying and similar processes.

Materials and Methods

Frying

Potato slices were cut into dimensions of 9.0 mm x 9.0 mm (Height x Width) by a manual French fry cutter and the length of each slice was adjusted to 70 mm using a knife. Frying experiments were conducted at temperatures of 150, 170, and 190°C in a temperature controlled electrical fryer (Sinbo, Model SDF-3804, China) of 1.0 L capacity using sunflower seed oil in four replicates for temperature and two replicates for moisture measurements.

Temperature and moisture measurements

Temperature was recorded every 30 s for frying temperatures of 150 and 170°C and every 15 s for 190°C at the center using a K-type thermocouple. The oil temperature was also checked using another thermocouple. For temperature experiments one slice was used at a time. Moisture content was determined by drying potato slices, sampled at 0, 30, 60, 90, 120, 150, 210, and 270 s of frying, to constant weight at 105°C.

Heat and mass transfer models

In order to characterize the temperature and moisture changes, each potato slice was modeled using partial differential equations accompanied with appropriate initial and boundary conditions as follows: For temperature, the general heat equation is;

$$\rho\, C\, \frac{\partial T}{\partial t} + \nabla.(-k\nabla T) = 0 \tag{1}$$

For moisture distribution the diffusion equation is:

$$\frac{\partial c}{\partial t} + \nabla.(-D\nabla c) = 0 \tag{2}$$

Figure 1 shows a 3-D-geometry of the potato slices used in experimentation. Because the height and width of each slice are equal and the hot oil is equally surrounded the slices, use of symmetry allows us to reduce this to 2-D-geometry. Further symmetry in the cross section makes it also possible to model only one quarter of the geometry as shown in the shaded section (Figure 2). Both simplifications result in a 2-D-rectangular domain with dimensions of 4.5x35 mm (HxL), as presented in Figure 2.

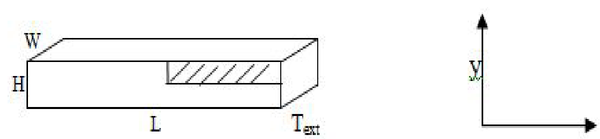

Figure 1: Geometry of the potato slice.

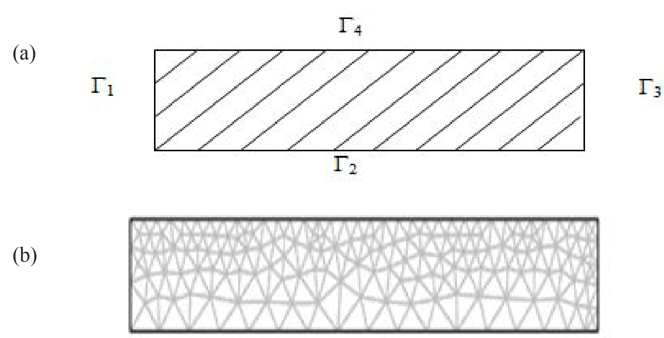

Figure. 2: A 2-D-View of system domain: a) Regular rectangular structure b) meshed structure

The boundary conditions for the general heat transfer mode are;

$$n(-k\nabla T) = 0 \text{ at } \Gamma_1 \text{ (axisymmetry)} \quad (3)$$

$$n(-k\nabla T) = 0 \text{ at } \Gamma_2 \text{ (insulation)} \quad (4)$$

$$n(k\nabla T) = h(T_{ext} - T) + n(D\lambda\nabla c) \text{ at } \Gamma_3 \text{ and } \Gamma_4 \quad (5)$$

The boundary conditions for moisture diffusion are;

$$n(-D\nabla c) = 0 \text{ at } \Gamma_1 \text{ and } \Gamma_2 \quad (6)$$

$$n(D\nabla c) = \frac{h}{\rho C}(c_b - c) \text{ at } \Gamma_3 \text{ and } \Gamma_4 \quad (7)$$

$$\text{where } k_c = \frac{h}{\rho C} \quad (8)$$

The initial conditions for heat and moisture variation are;

$$T(O,x,y) = T_o \text{ and } c(O,x,y) = c_o \quad (9)$$

The values and/or expressions of the physical parameters obtained from the literature to solve the coupled system of equations are listed in Table 1. The heat transfer coefficient (h) given in Eq. (8) was determined according to a methodology suggested by Hubbard and Farkas [7]. This methodology is simply based on measurements of potato surface temperature, oil temperature, and the water loss rate and substitution of these values into Eq. (10) to calculate the heat transfer coefficient. Thus, h can be expressed as a function of time or surface temperature of a potato slice and plugged into systems of equations.

Component	Definition	Value or expression	Reference
p	Density	1090	[8]
C	Heat capacity	3517	[8]
k	Thermal conductivity	1.05-1.96x10-2T+1.9x10-4T2	[15]
D	Diffusivity	9.2x10-9(150°C),11.0x10-9 (170°C), 18.2x10-9(190°C)	[8]
λ	Latent heat of vaporization	2257	[16]

Table 1: Values of parameters found from literature for the model.

$$h = \frac{dm}{dt}\frac{\lambda_{vap}}{A(T_{oil} - T_s)} \quad (10)$$

FEM Analysis

Heat transfer equation coupled with moisture diffusion equation was solved using Heat Transfer Module of COMSOL Multiphysics 3.3a (Stockholm, Sweden), a package program based on finite element method. A 2-D-rectangular coordinate system with a triangular element mesh (total elements are 308, and number of degrees of freedom is 1354) was processed for global solution (Figure 2a,b). Temperature and moisture plots were generated and their values were computed for further statistical analyses using the post-processing menu of the software.

Statistical analysis

Difference measure test was used to compare model predictions to experimental values. This test involved calculation of coefficient of determination (R2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). RMSE was also further fractionated into systematic and unsystematic counterparts for better assessment of the source of variation between the experimental and predicted values for temperature and moisture (this further analysis is not given here).

Results and Discussion

Temperature and moisture

Frying experiments were conducted to validate the FEM predictions. Potato slices of 9.0mm thick and 70mm long, as mentioned before were fried at temperatures of 150, 170, and 190°C. Temperature was measured at the center location and the results are given in Figures 3. A rapid temperature rise from initial levels of 14-15°C to ≥100°C was observed at all frying temperatures. The center temperature remained at about 101-107°C throughout the frying experiments (Figures 3). This observation was attributed to the high interior moisture, which prevented temperatures from increasing to higher level (see also Figures 4). Similar temperature profiles were reported in other studies [5,6,8].

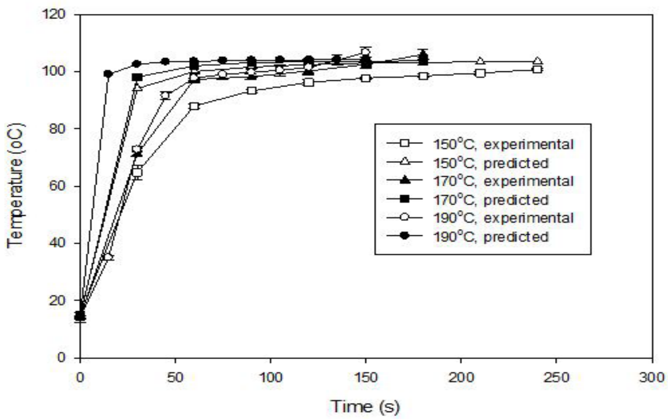

Figure 3: Experimental and predicted center temperatures of potato slices during frying at 150, 170, and 190°C for the first 240, 180, and 150 s, respectively.

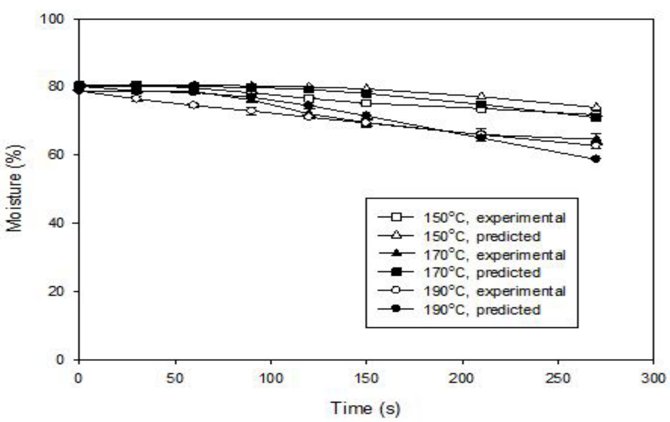

Figure 4: Moisture contents of potato slices during frying at 150, 170, and 190°C.

Initial moisture content of potato slices ranged between 79 and 81% and decreased to about 63-72% after 270 s of frying process (Figures 4). Higher moisture drop was observed at higher frying temperature (e.g. 190°C) because an increase in temperature increases the kinetic energy of water molecules, which enhances the moisture removal in the form of vapor. The moisture loss rate reduced as frying proceeded. The moisture decrease observed in this study was opposite to the results of Sahin et al. [5], who observed lower moisture levels due to using thinner potato slices (3mm) but similar to results of Farinu and Baik [6].

FEM simulation results

FEM simulation results of temperature and moisture values are also presented in Figures 3 and 4, respectively. A rapid initial change in temperature, as observed in experimental results, was successfully simulated by the model. However, the initial rate of increase differed from the observed data. The variation between experimental and predicted data was similar for frying temperatures of 150°C (R2=0.910 and RMSE=11.5°C) and 170°C (R2=0.915 and RMSE=10.6°C) but higher for 190°C, which possessed higher RMSE values (18.3°C) and lower R2 values (R2=0.718). The maximum temperature and the final steady state values reached agreed well for all frying temperatures (Figures 3). The larger deviation at 190°C could be attributed to the limitation of the constructed model, which assumed no change in surface conditions through the course of frying process. According to the study of Costa et al. [2], at higher frying temperatures the water loss rate is higher and results in vapor bubbles on the surface, which present an additional resistance to heat transfer from oil to the center. In contrast, if the bubbles flow away from the surface, the resulting increased motion at high water loss rate increases the heat transfer coefficient (h). Furthermore, the reported h-values in the literature are between 250 and 300 W/m2K for a temperature range of 170-190°C in the absence of bubbling and greater about 40 to 80% of these values in the case of bubbling [2,14]. Therefore, high values of heat transfer coefficient can mimic desirable bubble effect and low values approve the existence of the reverse effect. Because our calculated h-values are in the low region (366 to 62 W/m2K), the reverse bubble effect was concluded to exist and to cause the larger deviation between observed and predicted temperatures at frying temperatures of 170°C.

Measured moisture contents are compared to predicted values in Figures 4. The moisture content gradually decreased, as indicated by both experimental and predicted values. The model predictions remained higher than the measured values in all frying temperatures. The variation was the highest for mid-frying temperature of 170°C (R2=0.781, RMSE=0.06%, and MAE=0.05%) while the results for 150°C (R2=0.753, RMSE=0.03%, and MAE=0.02%) and 190°C (R2=0.910, RMSE=0.03%, and MAE=0.03%) agreed better to experimental values. It is well known that resistance to mass transfer is created by both internal resistances to mass diffusion and the surface resistance. In this study, a constant diffusivity coefficient for each frying temperature was considered and the values were taken from the study of Yildiz et al. [8] (See also Table 1). Thus, the predictions could be improved with the measured diffusivity values during frying process. The FEM model simulated frying temperatures of 150-170°C better than 190oC, which implies a need for improvement of the model for high temperatures. However, the moisture was predicted well in all conditions with low RMSE and MAE values. The results of this study indicated that the simplified FEM model can be used to predict temperature and moisture changes of potato slices during frying. The results also provide a basis for real time quality control and optimization.

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