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Multi-agent simulation of doughnut deep fat frying considering two domain heating media and sample flipping

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ABSTRACT

Two domain heating media and sample flipping during processing were considered when developing an agent-based model to explain coupled heat and mass transfer phenomena during deep fat frying of doughnuts. The model was validated by comparing the moisture content, oil content and temperature profiles obtained from the experimental results with those obtained from the model. Results of this study showed that the water content of crumb raised to 60% (based on dry weight) whereas, it decreased to less than 10% in the case of doughnut crust during deep fat frying. Simulated profile of oil penetration illustrated that the oil content of different parts of crust were not equal and were affected by frying temperature and crust structure. In general, as the surface of doughnut (a porous material) was heated from the surface, evaporation zones were formed in the thinner parts of the crust and gradually formed oil penetrating areas. Moreover, experimental and simulated data indicated that flipping of samples in the middle of processing time had an important effect on heat and mass transfer during frying. Variation of thermophysical properties in each part of doughnut had a unique behavior. The changes in the density, specific heat capacity and thermal conductivity of crumb followed a sigmoid pattern; whereas, a dominant falling rate period with some variations was observed in crust. Moreover, any changes in moisture content and temperature of crust occurred faster than the crumb. The output of simulation was in a good agreement with the experimental data. With the power of simulation now available for design, the results of this study greatly improve the design of fried foods and frying processes.

1. Introduction

Several parameters can affect fried food features such as the oil content, moisture content and structural changes during frying (Ghaitaranpour et al., 2024b; Sanz-Serrano et al., 2017; Tan and Mittal, 2006). Two of the most important parameters are the thermophysical properties and uniformity of the heating media. A specific heating media results in a two-sided heat transfer/one-sided frying of the products, where overheated areas and also uncooked regions are formed. This unwanted impact is very important and should be considered when designing a fryer (Sanz-Serrano et al., 2017). Furthermore, physical properties of a product (especially density) in some cases can also control its surrounding medium (Ghaitaranpour et al., 2018a).

The density of doughnut dough is approximately 950 kg/m^3, but it significantly decreases after the dough is fermented. At the beginning of the frying process, the structure of the doughnut becomes constant, and its density (480 kg/m^3) is approximately half of the density of the frying oil (Ghaitaranpour et al., 2018a); hence half of doughnut is immersed in hot oil whereas the other half is remained out of the oil medium and is surrounded by air. Therefore, in order to fry the upper side of doughnut, it must be turned over in the middle of the frying process (Ghaitaranpour et al., 2018a). There are limited studies regarding the modeling of a porous food during a two-sided heat transfer/one-sided frying process. Heat transfer in meat patties during single-sided pan-frying was modeled and solved by Finite Element Method (Ikediala et al., 1996). Considering food materials as porous structures, heat and mass transfers during processing in such materials have been illustrated in several studies using different mechanisms of mass and energy conservation. In some cases diffusion, convective and capillary transport phenomena, and physicochemical changes in the solid matrix were included (Halder et al., 2007a, 2007b, 2011; Khan et al., 2018). In another studies, pan-frying was modeled to study the physical behavior of the pancake (Feyissa et al., 2011; Sanz-Serrano et al., 2017). In these works, the internal structure of fried foods was assumed uniform, which is an unreal simplification in the case of highly porous media such as doughnut. Besides, in the mentioned models, the oil absorption during frying was

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not related to the internal structure of food. Hence, it is necessary to two-sided heat transfer/one-sided frying process and heterogeneity of food structure in a model which is more compatible with these conditions. An agent-based model (ABM) is a distributed artificial intelligence-based modeling technique to describe complex systems. It is based on the interactions among patches and agents (Bonabeau, 2002; Panait and Luke, 2005). This model can be applied to study and simulate nonlinear problems (Amaral and Ottino, 2004; Nicolis and Nicolis, 2012). ABM can simulate physical phenomena in more detail compared to the partial differential equations. Applications of ABM in the modeling of mass transfer phenomena were reported in some cases (O'Neil and Petty, 2013; Taherian et al., 2018; Zandi et al., 2017; Zandi and Mohebbi, 2015).

In our previous researches an agent-based model was used to study the heat transfer, water loss (Ghaitaranpour et al., 2020) and oil absorption (Ghaitaranpour et al., 2021) during the air frying of doughnuts. However, no comprehensive study has been done regarding the deep fat frying of doughnut in a two-sided heat transfer/one-sided frying medium. It should be noted that in the current study a two-domain heating medium was used and that the doughnuts were flipped over during the heating, which increases the complexity of doughnut frying. Therefore, the objective of the present study was to use an agent-based model containing a two-sided heat transfer/one-sided frying media of a domestic fryer, to describe the changes occur during the deep fat frying of doughnuts. This model allows the calculation of the physical properties, temperature and oil/water content in the doughnut along with its resulting physical properties. This research would extend the knowledge of what exactly happens during the deep fat frying of doughnuts in a domestic fryer.

Subscripts & superscript	
Oil content	Dry based oil content ($kg.kg^{-1}$)
m	Weight (kg)
ρ	Density ($kg.m^{-3}$)
V	Volume (m^3)
P	Pressure (atm)
P_{atm}	Atmosphere pressure
P_{sat}	saturated vapor pressure
A	Area of pores (m^2)
C_p	specific heat capacity ($J.kg^{-1}.K^{-1}$)
x, y	Distance (m)
T	Temperature (°C)
t	Time (S)
X	Dry based concentration ($kg.kg^{-1}$)
K	Thermal conductivity ($W.m^{-1}.K^{-1}$)
h_c	Surface heat transfer coefficient ($W.m^{-2}.K$)
h_L	Latent heat of vaporization($J.kg^{-1}$)
D	Diffusion coefficient ($m.s^{-1}$)
τ	Tortuosity
ε	Porosity
K_{Darcy}	Darcy coefficient
h_{mw}	Surface mass transfer coefficient ($kg.m^{-2}.S^{-1}.pa^{-1}$)
a_w	Water activity
T_∞	Hot air temperature (°C)
T_S	surface temperature of doughnut (°C)
ASO	Available surface oil
ABO	Absorbed oil
N	Number of inactive pores

Subscripts & superscript	
w	Water
$(oil), oil$	Oil
CHO	Carbohydrate
Prot	Protein
s	Dried matter
dough	Solid phase (Dough)
Dried_dough	Dough after variation in moisture content
Fried_dough	Dough after variation in oil content
Hot air	Hot air
$(v), v$	Water vapor
mint	Minimum value of the parameter until t
t	Frying time
prosity	Porosity
i	Number of pore or desired component

2. Materials and methods

2.1. Doughnut production

The preparation of doughnut and the subsequent frying process were based on our earlier studies (Ghaitaranpour et al., 2018a, 2018b). In brief, dough preparation process was divided into three main steps. In the first step, solid ingredients composed of wheat flour, milk powder, salt, xanthan gum, sugar, vanilla, gluten, baking powder, and citric acid were mixed and added to the liquid phase containing oil, eggs, yeast and water. In the second phase, this mixture was continually kneaded with a mixer (HG550TMEM, Hügel, Neuss, Germany) for 15 min and dough was cut by a special doughnut template. Finally, in the last step, the samples were kept in an oven at 40 °C for 70 min to complete the leavening process of doughnut. Because of Archimedes' law, this results in a lower density, which causes them to float in the oil while frying. Doughnut were then fried in a deep fat fryer (HD9240/90, PHILIPS, China) at 150, 165 and 180 °C for 180, 360 and 480 s. The frying time in each step was divided into two equal parts. At the end of first part, doughnuts were turned upside down to fry the top surface (Ghaitaranpour et al., 2018a).

2.2. Surface oil removing

Surface oil of doughnut was removed by dipping it in hexane for 1 s right after each frying sections (van Koerten et al., 2015).

2.3. Water content of crust and crumb

Oven drying method was employed to measure the moisture content of doughnut (Ghaitaranpour et al., 2017, 2018b). In order to study the water transfer phenomenon in different parts of sample during processing, samples were immersed immediately in liquid nitrogen after each frying section to freeze completely. After freezing, doughnut crumb and crust were separated from each other to measure the moisture content of each part.

2.4. Oil penetration during frying

Oil penetration during frying was measured after removing the adhered surface oil of doughnut followed by oven drying. Dried parts of doughnut were grounded prior to oil content determination by the Soxhlet method (van Koerten et al., 2015).

2.5. Temperature profile

The temperatures of top crust, bottom crust and the center of doughnut were monitored by three K-type thermocouples. A data logger, received the signals from thermocouples and recorded doughnut temperature during frying process (Ghaitaranpour et al., 2018b).

2.6. Modeling and simulation

The heat and mass transfer were modeled using the methods developed by Ghaitaranpour et al. (2020) based on multi agent systems. This model is composed of three connected phenomena namely heat transfer, water transfer and oil absorption (Fig. 1A). More details is given in the following sections.

2.6.1. Problem description

Fig. 1 shows a schematic of the problem. The doughnut dough was assumed to be a porous media. Doughnut deep fat frying composed of three main phenomena (heat transfer, water transfer and oil absorption) strongly connected with each other. In the current study, G-M-K model

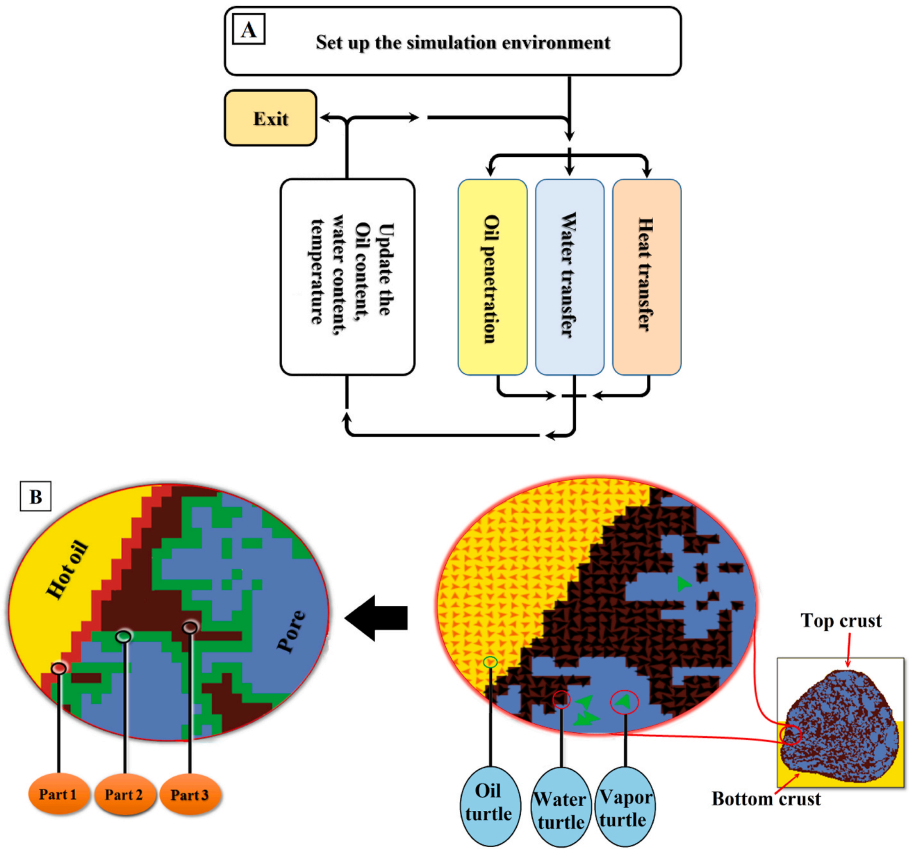

Fig. 1. A) Iteration steps for solving the frying model to evaluate the effect of doughnut deep fat frying behavior, B) A schematic diagram of doughnut; 1) outer layers of crust, 2) surface layer of pore walls 3) other parts of doughnut (dough solids).

(Ghaitaranpour et al., 2021) was used to describe the oil penetration mechanism during the deep fat frying of doughnut in which the heterogeneity of frying medium and flipping of samples during processing were taken into account. In this model, oil absorption pattern was strongly affected by the crust structure, water evaporation behavior and flipping of samples.

2.6.2. *Assumptions*

A number of assumptions need to be made for formulating the doughnut frying problem. The internal structure and volume of doughnut were assumed to be constant during the frying process. A thin layer doughnut cross section was considered as a 2D simulation environment divided into 22,801 tiny squares called patches. It was supposed that the simulation environment had two main regions named frying medium and doughnut area. The former one can be observed by yellow and white patches (8760 squares) in the model's platform (Fig. 1). The later one was a heterogeneous multiscale porous media composed of a solid phase (6608 patches) and porosity phase (7433 blue patches).

Porosity phase of doughnut cross-section was divided into 25 connected areas filled with water vapor. 18 out of 25 porosity area of doughnut was located in the crust region. The amount of water vapor in porosity phase can be changed depending on the frying time. Water vapor pressure was the only important feature in porosity phase. The pressure of each porosity area was computed using the Ideal gas pressure formula considering the volume of each area, the value of water vapor content of each area and the average temperature of water vapor turtles. The outcomes of the simulation remained largely unchanged even after increasing the number of patches and water vapor turtles.

Doughnut solid phase can be filled with solid fat free part of dough and/or liquid water and oil depending on the processing history. The current phase was divided into three different parts; 1: outer layer of crust, 2: surface layer of pore walls and 3: other parts of doughnut. Water and heat transfer of each part during hot air frying were modeled (discussed in detail in Equations section) according to our previous study (Ghaitaranpour et al., 2020). Thermal equilibrium was existed between all phases. There was an equilibrium between water in solid and water-vapor in porosity phases before frying; however, during frying, this equilibrium frequently changed and was replaced by new equilibrium conditions. Since bound water was not considered, all moisture content of doughnut was available for evaporation. Due to the small pore wall thickness, water diffusion in solid phase was considered negligible. Because the doughnut's structure stabilized early in the frying process, volume change during the process was also ignored.

Three types of turtles were considered in the current research. Each turtle had three main properties namely weight, temperature and energy. Each patch of solid phase contains a water turtle, which is the first type of turtle before frying. Water vapor turtles (the second type of turtles) were only found in porosity phase. The last type of turtles in this model are oil turtles, which were only present on the doughnut's surface when it first began to fry. However, as the doughnut fried, the oil turtles began to penetrate into the doughnut crust.

The crust was assumed as a series of tiny-squared-shape pores that connect the external parts of doughnut to the frying medium. The evaporation phenomenon caused the internal moisture to decrease, making the pore ready to absorb oil (van Koerten et al., 2015). Some additional assumptions should be used. The first one was that the pores which are expelling water vapor, cannot absorb oil since it doesn't have any free space for oil (inactive). Second, pores are spread over the doughnut's whole surface, and at the beginning of frying, all of them are active (have a considerable amount of water and they don't have any free space to absorb water) (Ghaitaranpour et al., 2021).

2.6.3. Governing equations

The model which is composed of three closely related submodels, consisted of heat transfer, water transfer and oil penetration. Doughnut medium was divided into three different parts to describe heat transfer easier: 1: outer layers of crust, 2: surface layer of pore walls and finally 3: other parts of doughnut. In the first part (Red patches in Fig. 1), 4 different mechanisms cooperated in heat transfer (Eq. (1))

$$\frac{\partial T_{dough}}{\partial t} = \underbrace{h_c A\left(\frac{T_{Hot\ air} - T_{dough}}{\rho C_p}\right)}_{A} + \underbrace{\frac{\partial}{\partial x}\left(\frac{K}{\rho C_p}\frac{\partial T}{\partial x}\right)}_{B} + \underbrace{\frac{\partial}{\partial y}\left(\frac{K}{\rho C_p}\frac{\partial T}{\partial y}\right)}_{C} + \underbrace{\frac{C_{p(oil)}\left(T_{oil} - T_{dough}\right)}{C_p\left(m_{Fried\_dough}\right)}\frac{\partial m_{oil}}{\partial t}}_{D} + \underbrace{\frac{h_L}{C_p}\frac{\partial X_w}{\partial t}}_{E} \quad (1)$$

where, part A is the temperature variation because of convective heat transfer, part B and C refer to the conductive heat transfer in x and y directions, part D and E are related to the crust temperature variation because of oil penetration and water evaporation phenomenon.

In the second part (Green patches in Fig. 1), heat transfer within the doughnut occurs by four different mechanisms as described below (Eq. (2)).

$$\frac{\partial T_{dough}}{\partial t} = \underbrace{\frac{\partial}{\partial x}\left(\frac{K}{\rho C_p}\frac{\partial T}{\partial x}\right)}_{A} + \underbrace{\frac{\partial}{\partial y}\left(\frac{K}{\rho C_p}\frac{\partial T}{\partial y}\right)}_{B} + \underbrace{\frac{C_{p(oil)}\left(T_{oil} - T_{dough}\right)}{C_p\left(m_{Frired\_dough}\right)}\frac{\partial m_{oil}}{\partial t}}_{C} + \underbrace{\frac{C_{p(v)}\left(T_v - T_{dough}\right)}{C_p\left(m_{Dried\_dough}\right)}\frac{\partial m_v}{\partial t}}_{D} + \underbrace{\frac{h_L}{C_p}\frac{\partial X_w}{\partial t}}_{E} \quad (2)$$

where, part A and B refer to the conductive heat transfer in x and y directions, part C and D are the temperature variation because of water vapor condensation and oil penetration, and part E refers to temperature change due to the water evaporation.

For part 3 which is the brown patches in Fig. 1, heat transfer mechanism is a combination of three sub-mechanisms as shown in eq. (3):

$$\frac{\partial T_{dough}}{\partial t} = \underbrace{\frac{\partial}{\partial x}\left(\frac{K}{\rho C_p}\frac{\partial T}{\partial x}\right)}_{A} + \underbrace{\frac{\partial}{\partial y}\left(\frac{K}{\rho C_p}\frac{\partial T}{\partial y}\right)}_{B} + \underbrace{\frac{C_{p(oil)}\left(T_{oil} - T_{dough}\right)}{C_p\left(m_{Fried\_dough}\right)}\frac{\partial m_{oil}}{\partial t}}_{C} + \underbrace{\frac{h_L}{C_p}\frac{\partial X_w}{\partial t}}_{D} \quad (3)$$

where, part A and B are conductive heat transfer in x and y directions, part B is the temperature variation because of oil penetration and part C refers to water evaporation.

Using the ideal gas law equation (Equ. 4), the water vapor pressure in each pore of the 25 porosity areas was calculated:

$$p_v = \frac{nRT}{V} \quad (4)$$

where, pv is the vapor pressure of the pore, V is the volume in m^3, n is the number of vapor turtles in mole, T is the temperature in Kelvin and R is the ideal gas constant (8.314 J/K·mol).

Three distinct phenomena were involved in the transfer of water during doughnut frying: Evaporation or condensation may take place in various doughnut sections to reach the vapor-liquid equilibrium. Water activity followed measured isotherm.

$$\frac{\partial X_w}{\partial t} = h_{mw}A\left(p_v - p_{sat,T_{Dough}}a_w\right) \quad (5)$$

A net movement of water vapor agents from a pore to its neighboring connected pore (because of concentration or pressure gradient) can be described as below:

$$\frac{\partial X_v}{\partial t} = \underbrace{\frac{\varepsilon D}{\tau}\frac{\partial^2 X_v}{\partial x^2}}_{A} + \underbrace{K_{Darcy}\frac{\partial^2 P_v}{\partial x^2}}_{B} \quad (6)$$

where, part A and B refer to diffusion and Darcy flow, respectively. In recent study, water diffusion in solid phase was neglected due to the low thickness of pore walls.

In current study, it was assumed that oil penetration into the doughnut crust during deep fat frying follows G-M-K model (Ghaitaranpour et al., 2021). In this model, oil is only taken up through the inactivated pores located in the external layer of doughnut crust. Following equation (6) we can relate the amount of water evaporation and the number of active pores using:

$$\begin{cases} W_{con} > W_{eva} & \rightarrow \quad \textit{Pore is active} \\ W_{con} \le W_{eva} & \rightarrow \quad \textit{Pore is inactive} \end{cases} \quad (7)$$

where, W_{con} represents the moisture content of a certain pore and patches surround it located in the connectivity radius and W_{eva} is the total amount of moisture evaporated from the pore and patches surround it in the connectivity radius. Since oil is only taken up through the inactivated pores, the amount of oil taken up by inactive pores using the amount of evaporated moisture is given by:

$$\textit{ABO for each active pore} = \begin{cases} ASO > \frac{m_w \rho_{oil}}{\rho_w} & \rightarrow \quad ABO = \frac{m_w \rho_{oil}}{\rho_w} \\ ASO = \frac{m_w \rho_{oil}}{\rho_w} & \rightarrow \quad ABO = \frac{m_w \rho_{oil}}{\rho_w} = ASO \\ ASO < \frac{m_w \rho_{oil}}{\rho_w} & \rightarrow \quad ABO = ASO \end{cases} \quad (8)$$

$$TOI = \sum_{i=1}^{N} ABO_i \quad (9)$$

where, TOI is the total oil uptake in an external layer of doughnut crust by inactive pores, N the number of inactive pores, ASO the amount of sprayed oil on the surface of each pore before hot air frying, ABO the amount of oil can be absorbed by an inactive pore considering the condition mentioned before. m_w the weight of evaporated moisture (kg) from a certain inactive pore, ρ_{oil} the density of oil (kg/m^3), and ρ_w is the density of water (kg/m^3).

Oil penetration from inactive pores into other layers of crust described by the following equation:

$$\frac{\partial C_{oil}}{\partial t} = D_{oil}\frac{\partial^2 c_{oil}}{\partial x^2} \quad (10)$$

where, C_{oil} is concentration of oil in each patch (kg/m^3), D_{oil} the oil diffusion coefficient (m^2/S) and x is the distance between the center of two connected patches (m).

The thermal properties of solid phase of doughnut as a function of temperature and composition of each patch were calculated (Phinney et al., 2017) after each predefined time period, known as ''tick'' in netlogo software. Specific heat capacity (Cp) and thermal conductivity (K) changed as temperature (T), carbohydrate (CHO), water (water), protein (prot) and oil (oil) content of each patches changed.

$$C_p = \sum_{i=1}^{n} X_i C_{pi} \quad (11)$$

$$C_{p_{Water}} = 4176.2 - 0.0909T + 5.4731 \times 10^{-3}T^2 \quad (12)$$

$$C_{p_{CHO}} = 1548.8 - 1.9625T + 5.9399 \times 10^{-3}T^2 \quad (13)$$

$$C_{p_{Prot}} = 2008.2 - 1.2089T + 1.3129 \times 10^{-3}T^2 \quad (14)$$

$$C_{p_{oil}} = 1984.2 - 1.4373T + 4.8008 \times 10^{-3}T^2 \quad (15)$$

$$K = \sum_{i=1}^{n} X_i K_i \quad (16)$$

$$K_w = 5.7109 \times 10^{-1} - 1.7625 \times 10^{-3}T + 6.7036 \times 10^{-6}T^2 \quad (17)$$

$$K_{CHO} = 2.0141 \times 10^{-1} - 1.3874 \times 10^{-3}T + 4.3312 \times 10^{-6}T^2 \quad (18)$$

$$K_{prot} = 1.7881 \times 10^{-1} - 1.1958 \times 10^{-3}T + 2.7178 \times 10^{-6}T^2 \quad (19)$$

$$K_{oil} = 1.8071 \times 10^{-1} - 2.7604 \times 10^{-4}T - 1.7749 \times 10^{-7}T^2 \quad (20)$$

Density (ρ) was expressed by the following equation:

$$\rho = \sum_{i=1}^{n} m_i \Big/ V \quad (21)$$

2.6.4. Boundary condition for heat transfer

Based on how the donut temperature changed, the frying time was divided into intervals of four to 12 min. The surface heat transfer coefficient was estimated using the below equation (Farinu and Baik, 2008).

$$h = \frac{MC_p\frac{dT}{dt} + L_v\frac{dX_w}{dt}}{A(T_\infty - T_S)} \quad (22)$$

where, part A and B refer to the energy used to increase the temperature of doughnut and to evaporate a part of its moisture content, respectively.

2.6.5. Initial conditions

Initial oil content, temperature, moisture and dry matter ratio of samples were measured before frying and applied to the model before the start of simulation. Equation (23) describes the initial conditions.

$$\begin{cases} T_{hot\ air} = Frying\ temperature \\ T_{dough} = T_w = T_v = Initial\ doughnut\ temperature \\ X_w = 0.32 \\ X_s = 0.68 \\ X_{oil} = 0.04 \end{cases} \quad (23)$$

To illustrate the effect of flipping over of doughnut on the behavior of oil absorption, water loss and heat transfer during frying, the doughnut's bottom and top (before flipping) were assumed to be surround with oil and air, respectively; hence, each part of doughnut had its own special features such as surface heat transfer coefficient, amount of oil which can be absorbed by doughnut and the temperature of surrounding medium. After the flipping, new situations were considered for both bottom and top parts of doughnut.

2.7. General algorithm and model solving

The model describing oil absorption, water loss and heat transfer during the deep fat frying process, was solved using the multi-agent systems (MAS) with NetLogo version 6.0.4. The procedure used in the Netlogo software to simulate oil absorption is composed of 4 sections (Taherian et al., 2018; Zandi et al., 2017).

The first part was a description of the global variables (turtles & patches). There were three types of turtles, which are waters, steams and oils. The main characteristics of these elements were weight (kg) and density (kg/m^3). The patches were divided into three different types consisting frying medium, solid-phase (dough phase), and pores phase. The solid phase was the most important type of patches, and its main features were the water and oil concentration (kg/m^3).

The second section was the description of the modeling environment structure. For this purpose, the image of a cross sectional-slice of the doughnut were imported to imageJ software bundled with 32-bit Java 1.6.0_05 followed by conversion to 8-byte type. The wall, pore and background of doughnut were separated using otsu method by thresholding (Ghaitaranpour et al., 2024a). Using this method, all possible threshold figures between the desired object and background are determined. The processed image was then imported to NetLogo software. The boundary of each pore was identified and used as a geometric model for simulation.

The next section was the setup process in which the simulation environment was prepared to begin the process, and the final step was "Go" process, which controlled the running of the model until it reached the desirable conditions (Fig. 4). Sliders, buttons, and switches in the NetLogo platform can control the process (Taherian et al., 2018; Zandi and Mohebbi, 2015). During or at the end of the simulation procedure, the planned algorithm can collect the required data of the model (Fig. 4).

2.8. Model validation

After the simulation process of oil absorption, output data were extracted and sent to Microsoft Excel spreadsheets. Two parameters consisting of Coefficient of determination (r), and Root Mean Square Error (RMSE), which are statistical parameters for model validation were calculated using the model and experimental data.

2.9. Data analysis

After the simulation of frying process, output data were extracted and sent to Microsoft Excel spreadsheets. Two parameters consisting of Coefficient of determination (r) and Root Mean Square Error (RMSE) which are statistical parameters for model validation were calculated based on the model and experimental data.

3. Results and discussion

Fig. 2 describes the simulated temperature, moisture and oil distribution within the cross-section of doughnut during frying at 180 °C for 0–180 s. Heat and mass transfer in porous materials is a complicated problem especially when the heating medium is not homogenous. Doughnut is a highly porous medium (Ghaitaranpour et al., 2018a, 2018b) and transfer phenomena during deep fat frying are more complicated in these types of structures compared with the air frying method. Because of its highly porous structure, doughnut should be flipped from one side to the other side in the middle of frying process to fry the top surface. The bottom and top surfaces of the doughnut (before flipping) were assumed to be surrounded by oil and air, respectively, in order to explain the effect of heterogeneity in the frying medium and sample flipping on the behavior of doughnut frying. This meant that each part of the doughnut had a unique surface heat transfer coefficient, the amount of oil it could absorb, and the temperature of the surrounding medium.

3.1. Temperature

3.1.1. Effect of domestic fryer heating media on temperature profile of crust

As discussed in our previous studies, the top and bottom crust has different thermal history during frying (Ghaitaranpour et al., 2018a, 2018b). A rapid increase in the temperature of bottom crust until 90 °C was observed after 30 s of frying. Bottom crust spends more time at temperature above 90 °C compared to the top crust. However, the temperature of top crust raised to about 42 °C before flipping and to 125 °C after flipping which was approximately 20 °C higher than the maximum temperature of the bottom crust (Fig. 3).

3.1.2. Temperature profile of doughnut crumb

The temperature profile for doughnut crumb can be divided into three stages (Fig. 4A). At the beginning of the frying process, the first stage started and continued for about 40 s. In this case, the maximum temperature of crumb was around 35 °C, while at the same time, the top and bottom surfaces temperatures were around 36 °C and 95 °C,

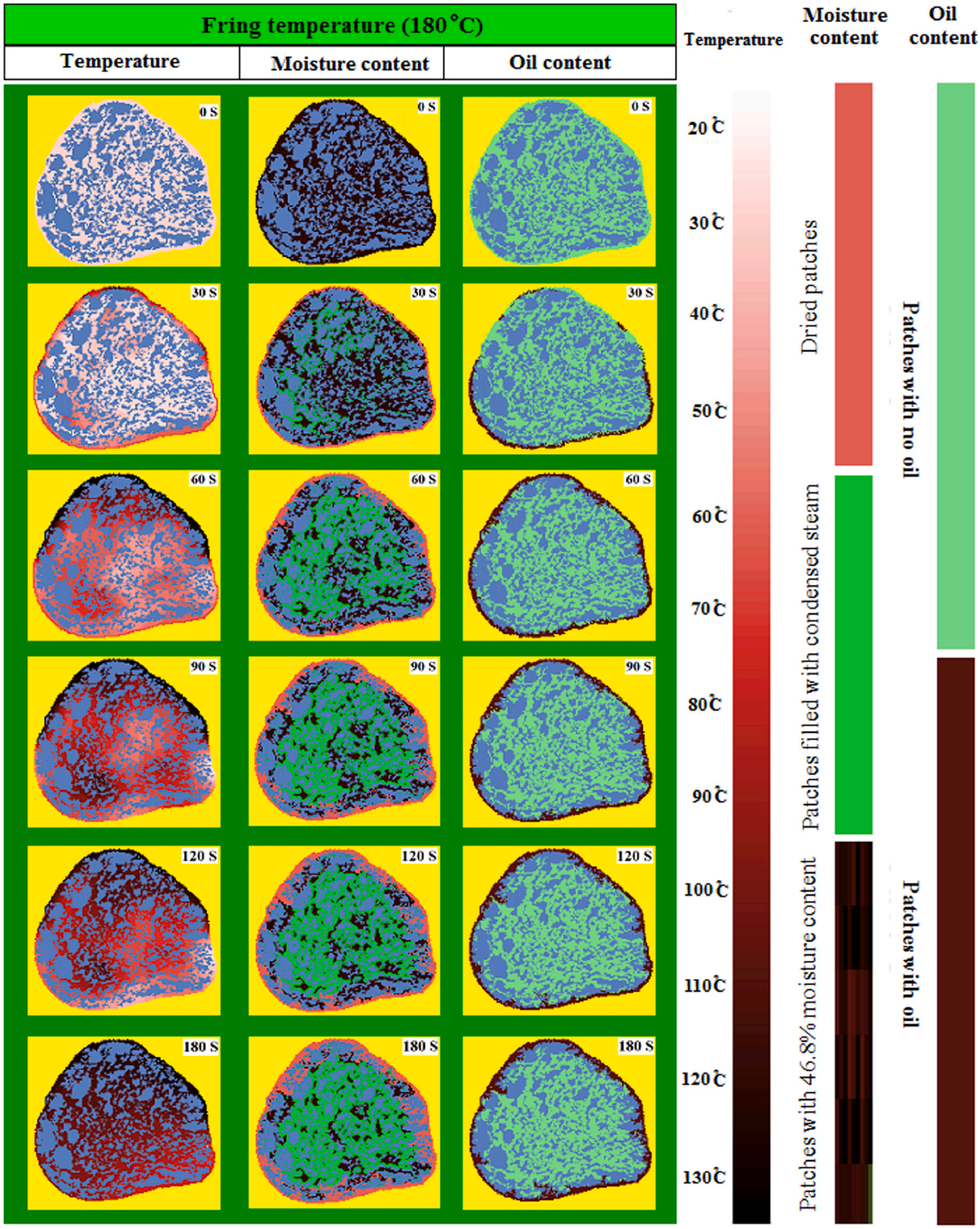

Fig. 2. Simulation of temperature, water and oil distributions during the frying process.

respectively. The second stage started when the temperature of the crumb reached to 40 °C which is equal to the average temperature of the top crust. In this step, the crumb temperature was higher than the top crust temperature due to the receipt of large amount of thermal energy from the bottom surface of doughnut. This stage ended by flipping the doughnut at the middle of the frying process. The crumb temperature showed a plateau at around 98 °C in the final stage of processing which was the longest part of doughnut frying. This procedure is in agreement with our previous findings (Ghaitaranpour et al., 2018a, 2018b). In this stage, maximum temperatures of top crusts reached to 105 °C or more, depending on the processing temperature; while the bottom surface of doughnut showed a plateau at around 100 °C. This plateau is linked to the flipping of the doughnut which was done in the middle of the frying process.

3.1.3. Estimated temperature of water vapor in crumb and crust pores

Predicted water vapor temperature in deep fat fried doughnut had a complicated pattern (Fig. 4B); whilst the change of water vapor temperature in air-fried doughnut had simpler pattern because of the homogenous heating media in this fryer. The vapor temperature increase

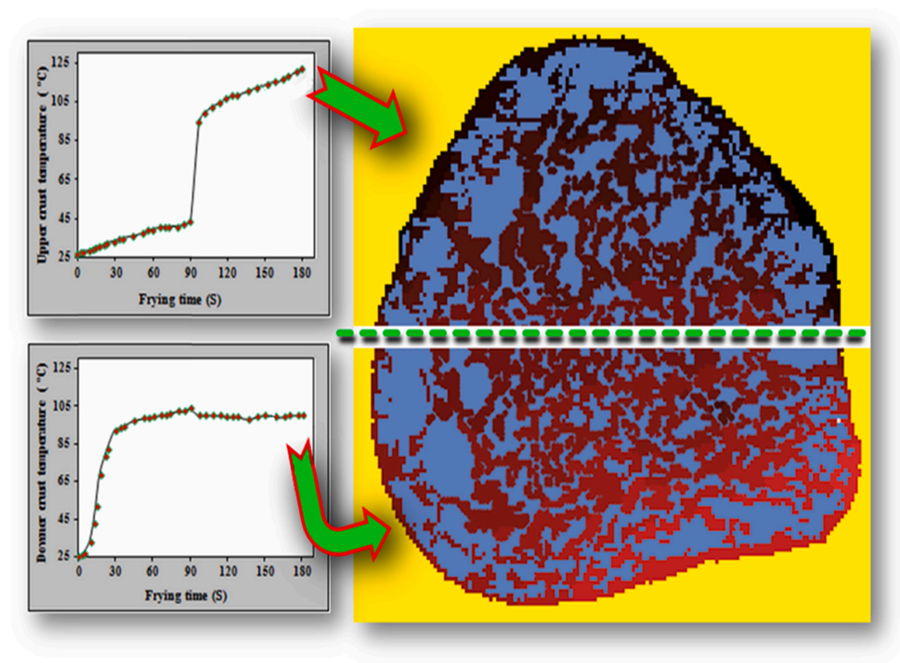

Fig. 3. Thermal history of top and bottom crust.

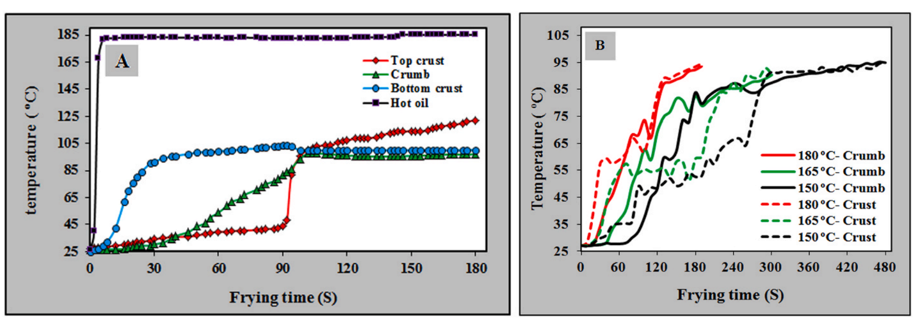

Fig. 4. A) Experimental temperature of doughnut during frying (180 °C); B) Predicted temperature of water vapor in crumb and crust pores.

in both crumb and crust sections, followed a sigmoid behavior during the frying. They gradually increased to 40 °C, then rapidly reached to around 80 °C in less than 120 s and finally reached to a temperature plateau at about 95 °C. Although they had a same behavior, the temperature of the crust was approximately 2 °C greater than the crumb.

At the beginning of deep fat frying process in a domestic fryer heating media, steam temperature reached to around 55 °C in 60–120 s depending on the frying conditions (Fig. 4B). In this stage, steam temperature of crust was averagely 5 °C higher than that of crumb. However, in the middle of frying, the trend reversed and temperature of the water vapor in the crumb increased rapidly from 55 °C to 85 °C. During this period, the vapor temperature of crumb was almost 7 °C greater than the average vapor temperature of both bottom and top crust. However, at the end of process the steam temperature in both parts were almost the same and reached to around 94 °C. This could be due to the heterogeneity in the frying medium and flipping of doughnuts at the middle of the frying process.

3.2. *Moisture content*

3.2.1. *Total moisture content*

Fig. 5A represents the water loss behavior of doughnut during deep fat frying. Drying of doughnut can be divided into two totally different phases. The total moisture content rapidly decreased from 46.9% (db) to about 42% (db) in the first phase, while the second phase had a gradual decreasing trend. In the last phase, total water content decreased to 39% (db). The results of this research were in a good agreement with those reported by other researchers (Tan and Mittal, 2006; Vélez-Ruiz and Sosa-Morales, 2003). Ghaitaranpour et al. (2020) also reported the same manner in the case of water loss during doughnut hot air frying.

3.2.2. *Crumb and crust moisture content*

The moisture content of crust decreased from 46.9% (db) to less than 9% (db) with increasing the frying time (Figs. 2 & 5B). Furthermore, water content of crust was strongly affected by the frying temperature. With increasing the frying temperature, the water evaporation raised as evidenced by a decrease in the moisture content (Fig. 5B). This finding was in good agreement with our previous research on the air frying of doughnut (Ghaitaranpour et al., 2020). For air fried doughnut, the moisture content of crust decreased continuously and due to the higher frying temperature, faster moisture loss from doughnut surface was observed (Ghaitaranpour et al., 2020).

As shown in Fig. 5C, crumb water content increased rapidly from 46.9% to around 59% (db) during the frying process. The change in the water content of doughnut crumb had sigmoid behavior. There were two constant phases in the beginning and end of the frying process with an increasing phase between these two phases. The last phase is related to the vapor condensation in the doughnut crumb (Ghaitaranpour et al.,

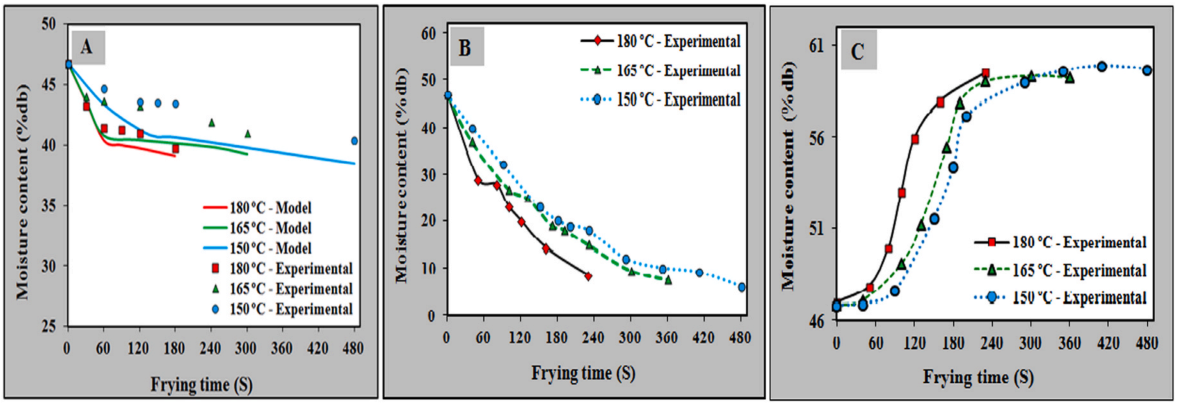

Fig. 5. Experimental and simulated moisture content of doughnut during frying (180 °C); A) Total moisture content, B) Crust moisture content, C) Crumb moisture content.

2020). Our findings were in agreement with other studies (Lucas et al., 2015; Wagner et al., 2007) who also reported a slight increscent of moisture content in the bread crumb during baking. The increase in the moisture content at the center of doughnut during frying is due to a phenomena called evaporation-diffusion-condensation which occurs in porous materials (Halder et al., 2007a, 2007b, 2011; Lucas et al., 2015; Wagner et al., 2007). Increasing the frying temperature exacerbated the effect of this phenomenon.

3.2.3. *Effect of domestic fryer heating media on the moisture content of crust*

Simulated data for the water evaporation from the bottom and top crust showed that they had different water loss procedures (Fig. 6). At the beginning of the frying process, only the bottom crust contacted with hot oil; hence, evaporation rate in this part was much faster than the top crust and the moisture content decreased from 46.9 (db) to 15% (db) after 150 s; whilst, at the same time, the top surface of doughnut lost only 30% of its initial moisture content which was almost a half of mass loss in the bottom crust. By flipping the doughnut in the middle of frying process, evaporation procedure changed and hence the water loss of top crust was faster (Fig. 6).

3.3. *Oil distribution pattern*

3.3.1. *Total oil content*

Figs. 2 and 7 illustrate the oil uptake during doughnut deep fat frying. The values approximately varied between 4 and 30 g/100 g dry matter for doughnut and in general, it could be said that the total fat content of samples increased during deep fat frying especially in the first 2 min of this process. Our findings were in agreement with the results of other researchers who indicated that the oil content of doughnut raised from about 8% to 16% on the wet basis when frying time increased (Vélez-Ruiz and Sosa-Morales, 2003). In the first steps, (0–30 s) the oil uptake increased rapidly, resulting from the replacement of evaporated water with oil. This phenomenon was also observed by other researchers for doughnut (Vélez-Ruiz and Sosa-Morales, 2003).

3.3.2. *Oil penetration into the doughnut crust during deep fat frying*

Total oil content of fried foods can be divided into three different fractions and each fraction has an individual absorption mechanism (Ouchon et al., 2003). Three types of oils were observed in doughnut, structural oil, penetrated surface oil and surface oil (Zhang et al., 2016). In this section, we only studied the structural oil which represents the oil that is absorbed during frying. As presented in our previous research, procedure of oil penetration in doughnut crust during air frying is

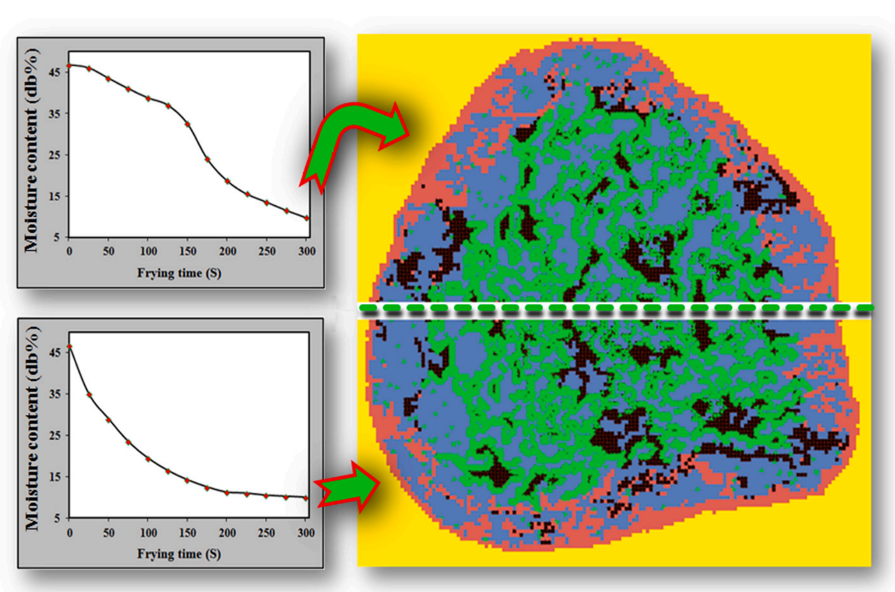

Fig. 6. Moisture content change of top and bottom crust.

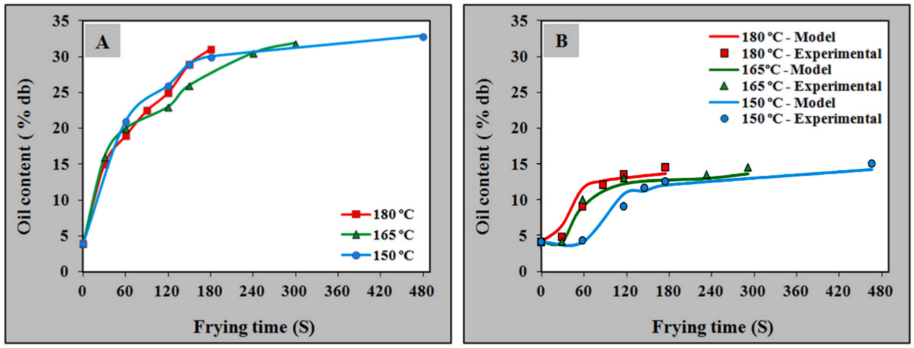

Fig. 7. A) Doughnut oil content during air frying; B) Experimental and simulation of oil penetration in doughnut crust during hot air frying.

composed of three successive phases named latent phase, acceleration phase and deceleration phase (Ghaitaranpour et al., 2020) which were also observed in the present study. Results showed that as frying progressed, larger amount of oil penetrated into the inner layers of doughnut crust (Figs. 2 and 7B). However, the frying temperature did not have any significant effect on the total oil content of doughnut while it can change the duration time of oil penetration phases (Fig. 7A and B). As frying temperature increased, the duration time of stationary parts of oil penetration curve (latent phase and deceleration phase) decreased whereas acceleration phase time remained constant. As a results, penetrated surface oil reached to approximately 14.5% which was equal for all samples at the end of frying process.

3.3.3. *Effect of fryer nonuniform heating media on oil content of the crust*

Simulated data showed that each part of bottom and top crust had its individual oil absorption procedures (Fig. 8). As mentioned above, at the beginning of frying process, only the bottom crust came into contact with hot oil and the evaporation rate in this part was much faster than the top crust. Therefore, the oil content of the bottom crust started to increase shortly after the frying began and hence the oil content increased from 4% to 12% after 150 s. By flipping the doughnut in the middle of frying process, evaporation procedure changed and, in this case, oil absorption by the top crust increased rapidly. The oil absorption history and a cross-sectional slice of doughnut at the end of the process can be observed in Fig. 8.

3.4. *Thermophysical properties*

3.4.1. *Doughnut thermophysical properties profile*

Three important parameters including density, specific heat capacity and thermal conductivity were considered in this study. Fig. 9 shows how these parameters changed during frying. From the figure, it could be seen that changing parameter's value in each part of doughnut had a unique behavior during frying. It seems that the decrease of these parameters in the crust took place in a progressive front. Hence, at the end of frying process, we had a crust with relatively uniform density, specific heat capacity and thermal conductivity around the inner parts. Variation in the thermophysical properties of doughnut crumb was more than that of crust region (Fig. 9). Due to special structure of crumb area, these changes did not occur in a progressive front.

Thermophysical features of doughnut during deep fat frying were studied by other researchers (Vélez-Ruiz and Sosa-Morales, 2003). They stated that the density and heat capacity of doughnut decreased and increased, respectively whereas, thermal conductivity and thermal

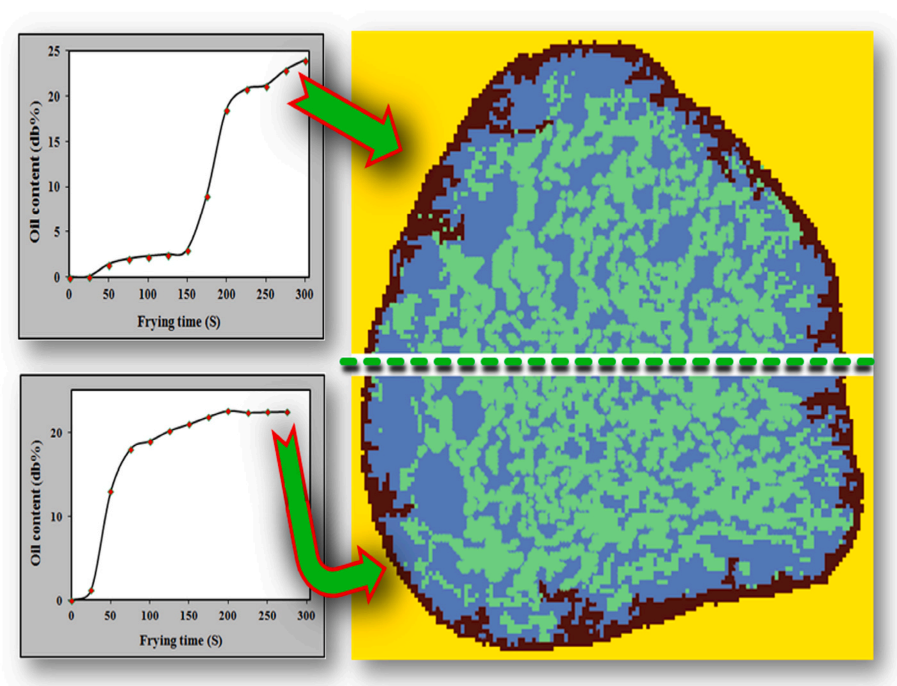

Fig. 8. Oil content simulation of top and bottom crust.

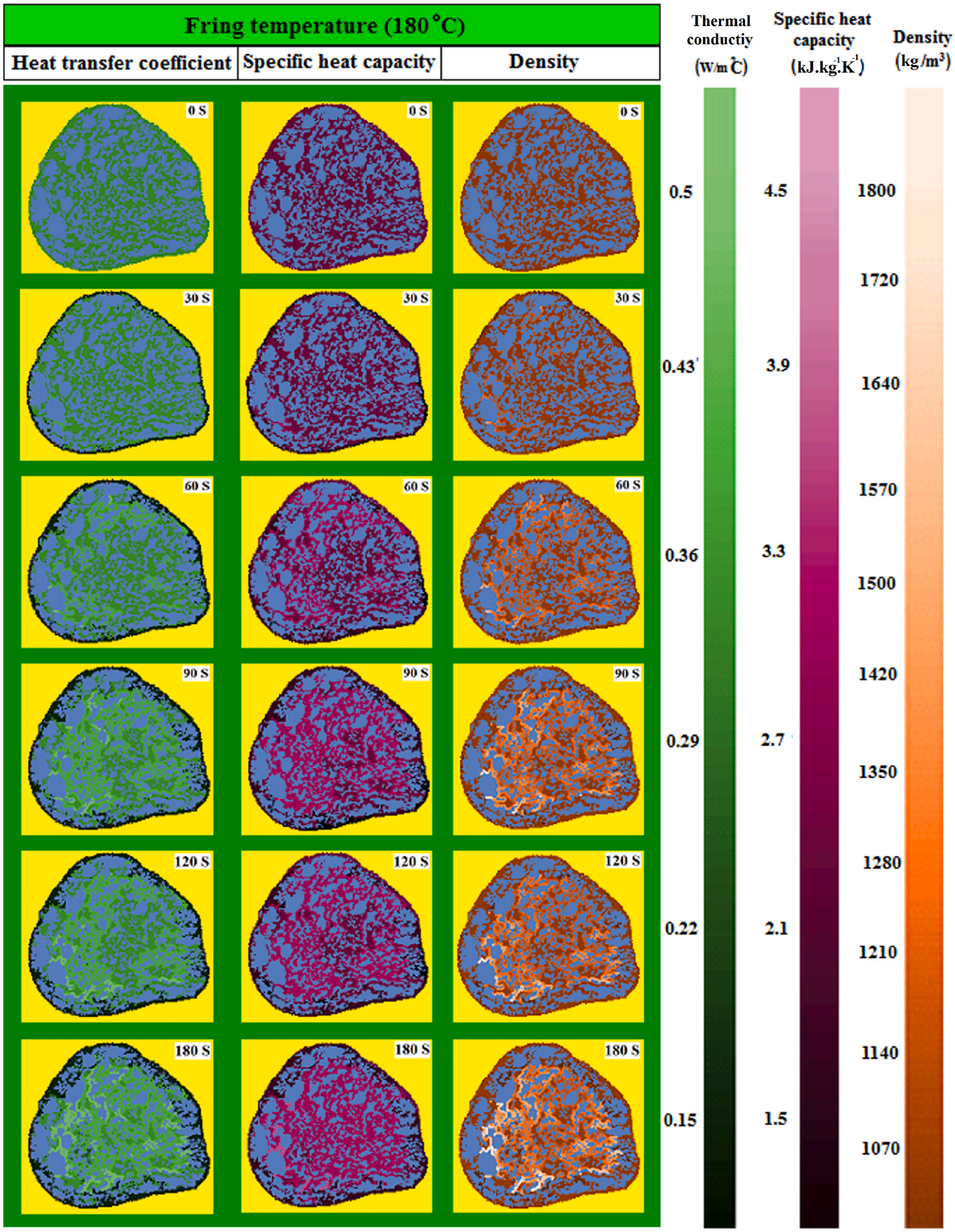

Fig. 9. Density, specific heat capacity and thermal conductivity simulation during frying process.

diffusivity did not change. It should be mentioned that these researchers did not study the thermophysical properties of crust and crumb separately so their results do not completely match with our findings.

3.4.2. Changes in crumb thermophysical properties

Density, specific heat capacity and thermal conductivity of crumb increased in the same way during the frying process. The behavior of these changes during frying followed a sigmoidal type pattern and in rising part of these pattern which is marked with a green arrow in Fig. 10, major variation of crumb thermophysical characteristics took place. Density, specific heat capacity and thermal conductivity reached from their initial values to 1390 (kg.m^{-3}), 2.7 (kJ.kg^{-1}.K^{-1}) and 0.00037 (kW.m^{-1}.k^{-1}), respectively. In contrast to our results, the thermal conductivity of crumb during frying of potato increased with increasing the frying time and reached to its maximum value after 3 min and decreased afterwards (Ziaiifar et al., 2009). This decrease in thermal

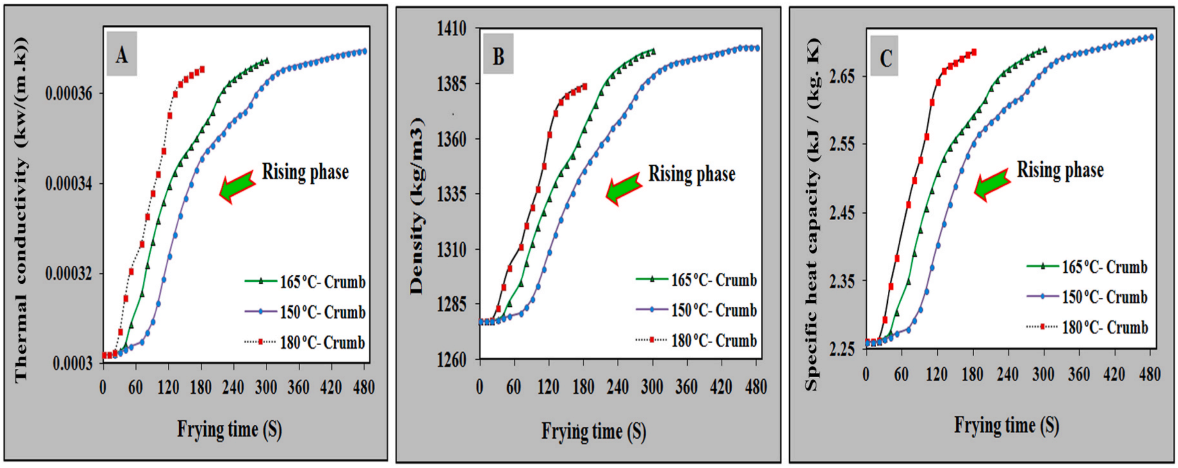

Fig. 10. Simulation of thermophysical properties of crumb during frying. A) Thermal conductivity, B) Density, C) Specific heat capacity.

conductivity was attributed to the moisture reduction in the final stages of frying.

As mentioned before, any change in composition and temperature of the target area affect the value of these features. Therefore, the sigmoidal behavior observed in Fig. 10 indicates that the temperature and composition (moisture content) of crumb have changed dramatically when rising phase of the sigmoidal behavior happens during frying. These observations are also confirmed by the pattern of temperature and moisture content change in the crumb of doughnut (Figs. 4 and 5). Other studies have also shown that the value of thermal conductivity increases with increase in water content (Halder et al., 2007b; Ziaiifar et al., 2009).

3.4.3. Changes in crust thermophysical properties

Fig. 11 shows how thermophysical properties of doughnut crust changed during frying at various temperatures. The pattern of change in crust thermophysical properties is more complicated compared with those of crumb. This is because of vigorous variation in moisture content, temperature and oil content of crust as frying progresses.

The behavior of changes in the thermophysical properties of doughnuts can be divided into three phases (which are marked with red, green and purple signs in Fig. 11). In the first phase, the density, specific heat capacity and thermal conductivity went down abruptly and reached from its initial value to around 1230 (kg.m^{-3}), 2.18 (kJ.kg^{-1}.K^{-1}) and 0.000286 (kW.m^{-1}.K^{-1}), respectively. This sudden decrease could be attributed to the rapid drop in moisture content of the doughnut surface (Fig. 5B). In a study on the modeling of restructured potato during frying, at the beginning of the process, liquid water saturation in the crust decreased and hence the thermal conductivity decreased (Halder et al., 2007b).

In the second phase, water loss, oil penetration and temperature change can affect the thermophysical characteristics of crust. Oil content and temperature of doughnut surface layers rose rapidly during phase 2 (Figs. 4 and 7B) and quickly increased the density and specific heat capacity of crust to 1245 (kg.m^{-3}) and 2.23 (kJ.kg^{-1}.K^{-1}), respectively. Up to 2.5% decrease depending on frying temperature was observed in the thermal conductivity after phase 1 (Fig. 11). Halder et al. (2007b) also reported that the thermal conductivity of crust slightly increases as oil from the surface reaches to this region.

In the third phase, oil content and temperature of crust were approximately constant (Figs. 4 and 7B); hence, water content was the only important feature which could change the thermophysical characteristics of crust. Variation in thermophysical features were directly affected by the moisture content in the doughnut crust. Other researchers also indicated that there is a direct relationship between the crust moisture content and the value of its thermal conductivity (Halder et al., 2007b; Ziaiifar et al., 2009). As can be seen in Figs. 10 and 11, the density, specific heat capacity and thermal conductivity reached to 1158 (kg.m^{-3}), 2.04 (kJ.kg^{-1}.K^{-1}) and 0.00021 (kW.m^{-1}.k^{-1}), respectively which were lower than that of the crust. Rask (1989) have also reported that the thermal conductivity and specific heat capacity of crumb were higher than those observed in the crust of similar products such as bread.

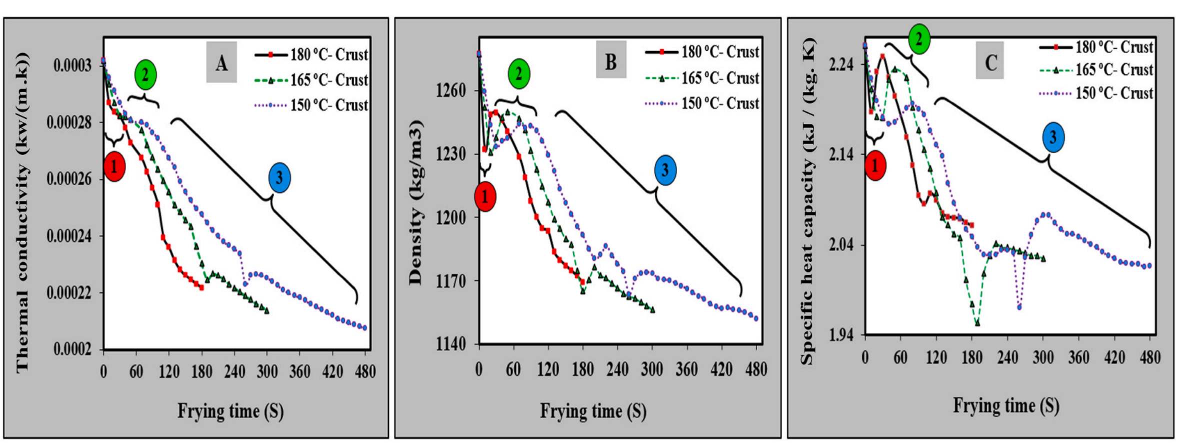

Fig. 11. Simulation of thermophysical properties of crust during frying. A) Thermal conductivity, B) Density, C) Specific heat capacity.

3.5. Critical factors that affect the performance of the model

3.5.1. Connectivity radius

As mentioned, the connectivity radius is the number of patches in a certain direction that can control the activation state of a patch. This parameter is the most important factor which controls the behavior of oil penetration into the doughnut (Ghaitaranpour et al., 2021). As the connectivity radius increased, the final amount of absorbed oil also increased. This can also affect the starting time of the oil penetration into the doughnut crust.

3.5.2. Diffusion of water vapor turtles

Brownian motion is the random motion of particles suspended in a medium (diffusion). An important part of heat and moisture transfer depends on the Brownian motion of water vapor turtles. During process simulation, as the temperature of doughnut increased during frying, the Brownian motion of water vapor turtles also increased.

3.5.3. Evaporation–condensation–diffusion phenomenon

The "evaporation–condensation–diffusion" phenomenon (ECD) is the last critical factor that affect the performance of the model. ECD is well known in baking process, but it is not commonly used in the frying process, because most fried foods have low porosity. This phenomenon increases the water content of the central part of bread and raises the rate of heat transport into it. Without considering ECD phenomenon the performance of the model decreases dramatically (Thorvaldsson and Janestad, 1999; Vries et al., 1988; Zhang et al., 2005).

3.6. Model validation

Validation of the model is one of the important steps in simulation of different phenomena especially in the field of food processing. Ranges of frying temperatures (150–180 °C) were used to investigate the effect of oil temperature on heat and mass transfer during deep fat frying. The temperature of all parts of samples increased with increasing the frying time and temperature. Based on Fig. 12, the trend of changes in temperature of top crust, crumb and bottom crust were well predicted by the model presented in this study. The model correlation coefficients (r) and root mean square errors (RMSE) are presented in Table 1.

In this work, oil and moisture content were also measured at different parts of doughnut. There was a positive correlation between the experimental and simulated temperature, oil and moisture content data (Figs. 5A and 7B), with the correlation coefficients above 80%. Result also showed that this model was able to predict the heat and mass transfer successfully during complicated processes such as deep fat frying of doughnut (Table 2).

Table 1
Results for the statistical analysis of the temperature using agent based frying models.

Location	Temperature (°C)	Correlation coefficient (r)	Root Mean Square Error (RMSE)
Upper crust	180 °C	0.96	11.03
	165 °C	0.98	6.48
	150 °C	0.98	5.05
Crumb	180 °C	0.96	10.24
	165 °C	0.93	11.85
	150 °C	0.88	14.63
Lower crust	180 °C	0.80	15.29
	165 °C	0.82	17.72
	150 °C	0.93	13.34

Table 2
Results for the statistical analysis of water and oil content using agent based frying models.

Mass type	Temperature (°C)	Correlation coefficient (r)	Root Mean Square Error (RMSE)
water content	180 °C	0.94	0.9
	165 °C	0.80	2.0
	150 °C	0.85	2.1
Oil content	180 °C	0.88	1.3
	165 °C	0.99	0.7
	150 °C	0.96	0.8

4. Conclusion

An agent based two-dimensional model has been proposed for heat and mass transfer in doughnut during deep fat frying. The major contribution of this study was the addition of a fryer heating medium to the modeling of doughnut deep fat frying, inspired by the real situation exists in domestic fryers. Thus, the influences of the heterogeneity of heating media and flipping of doughnut in the middle of frying process were also included in the model. Since, agent-based models can simulate complex systems, therefore it can be used for estimation of temperature, thermophysical properties, water and oil content of doughnut when using a domestic frying condition for samples preparation. In addition, simulated data showed that the water content of doughnut crumb rises during deep fat frying because of the difference in the vapor pressure between crust and crumb. It was also observed that during deep fat frying of doughnut, the temperature between vapor and dough phase of crumb was different. Results indicated that the oil penetration into crust was affected by the frying temperature. The down crust started to absorb the oil earlier than the top crust. Temperature profile for different part of doughnut also showed that at the end of frying process, the top crust temperature was higher than the downer part. Moreover, it was

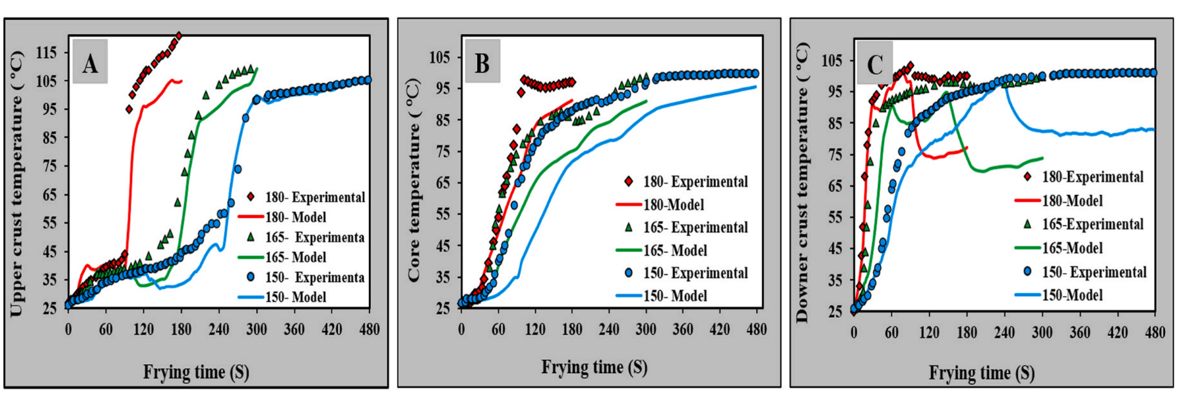

Fig. 12. Simulated and experimental temperature within doughnut during frying, A) Temperature of top crust; B) Crumb temperature; C) temperature of bottom crust.

observed that the thermophysical properties (density, specific heat capacity and Thermal conductivity) in doughnut crumb and crust increased and decreased during frying, respectively. Due to the flexibility and unique features of this model, it can successfully be used for other types of frying techniques.

CRediT authorship contribution statement

Arash Ghaitaranpour: Formal analysis, Methodology, Software, Writing – original draft. **Arash Koocheki:** Conceptualization, Supervision, Writing – review & editing. **Mohebbat Mohebbi:** Conceptualization, Supervision, Software.

Declaration of competing interest

The author declare that they have no conflict of interest.

Data availability

The authors do not have permission to share data.

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References

Amaral, L.A.N., Ottino, J.M., 2004. Complex networks. Eur. Phys. J. B Condens. Matter 38, 147–162. https://doi.org/10.1140/epjb/e2004-00110-5.

Bonabeau, E., 2002. Agent-based modeling: methods and techniques for simulating human systems. Proc. Natl. Acad. Sci. USA 99, 7280–7287. https://doi.org/10.1073/pnas.082080899.

Farinu, A., Baik, O.-D., 2008. Convective mass transfer coefficients in finite element simulations of deep fat frying of sweetpotato. J. Food Eng. 89, 187–194. https://doi.org/10.1016/j.jfoodeng.2008.04.024.

Feyissa, A.H., Gernaey, K.V., Ashokkumar, S., Adler-Nissen, J., 2011. Modelling of coupled heat and mass transfer during a contact baking process. J. Food Eng. 106, 228–235. https://doi.org/10.1016/j.jfoodeng.2011.05.014.

Ghaitaranpour, A., Koocheki, A., Mohebbi, M., 2024a. Simulation of bread baking with a conceptual agent-based model: an approach to study the effect of proofing time on baking behavior. J. Food Eng. 368, 111920 https://doi.org/10.1016/j.jfoodeng.2023.111920.

Ghaitaranpour, A., Koocheki, A., Mohebbi, M., Ngadi, M.O., 2018a. Effect of deep fat and hot air frying on doughnuts physical properties and kinetic of crust formation. J. Cereal. Sci. 83, 25–31. https://doi.org/10.1016/j.jcs.2018.07.006.

Ghaitaranpour, A., Mohebbi, M., Koocheki, A., 2021. An innovative model for describing oil penetration into the doughnut crust during hot air frying. Food Res. Int. 147, 110458 https://doi.org/10.1016/j.foodres.2021.110458.

Ghaitaranpour, A., Mohebbi, M., Koocheki, A., 2018b. Characterizing the cellular structure of air and deep fat fried doughnut using image analysis techniques. J. Food Eng. 237, 231–239. https://doi.org/10.1016/j.jfoodeng.2018.06.006.

Ghaitaranpour, A., Mohebbi, M., Koocheki, A., Ngadi, M.O., 2020. An agent-based coupled heat and water transfer model for air frying of doughnut as a heterogeneous multiscale porous material. Innovat. Food Sci. Emerg. Technol. 61, 102335 https://doi.org/10.1016/j.ifset.2020.102335.

Ghaitaranpour, A., Mohebbi, M., Oleyaei, S.A., 2024b. Effects of coating formulation on structural changes of Turkey nugget during frying: MRI evaluation. J. Funct.Foods 4, 142–148. https://doi.org/10.1016/j.jfutfo.2023.06.005.

Ghaitaranpour, A., Rastegar, A., Tabatabaei Yazdi, F., Mohebbi, M., Alizadeh Behbahani, B., 2017. Application of digital image processing in monitoring some physical properties of Tarkhineh during drying. J. Food Process. Preserv. 41, e12861 https://doi.org/10.1111/jfpp.12861.

Halder, A., Dhall, A., Datta, A.K., 2011. Modeling transport in porous media with phase change: applications to food processing. J. Heat Tran. 133 https://doi.org/10.1115/1.4002463.

Halder, A., Dhall, A., Datta, A.K., 2007a. An improved, easily implementable, porous media based model for deep-fat frying. Food Bioprod. Process. 85, 209–219. https://doi.org/10.1205/fbp07033.

Halder, A., Dhall, A., Datta, A.K., 2007b. An improved, easily implementable, porous media based model for deep-fat frying. Food Bioprod. Process. 85, 220–230. https://doi.org/10.1205/fbp07034.

Ikediala, J.N., Correia, L.R., Fenton, G.A., Ben-Abdallah, N., 1996. Finite element modeling of heat transfer in meat patties during single-sided Pan-frying. J. Food Sci. 61, 796–802. https://doi.org/10.1111/j.1365-2621.1996.tb12205.x.

Khan, M.I.H., Joardder, M.U.H., Kumar, C., Karim, M.A., 2018. Multiphase porous media modelling: a novel approach to predicting food processing performance. Crit. Rev. Food Sci. Nutr. 58, 528–546. https://doi.org/10.1080/10408398.2016.1197881.

Lucas, T., Doursat, C., Grenier, D., Wagner, M., Trystram, G., Flick, D., 2015. Modeling of bread baking with a new, multi-scale formulation of evaporation–condensation–diffusion and evidence of compression in the outskirts of the crumb. J. Food Eng. 149, 24–37. https://doi.org/10.1016/j.jfoodeng.2014.07.020.

Nicolis, G., Nicolis, C., 2012. Foundations of Complex Systems. WORLD SCIENTIFIC. https://doi.org/10.1142/8260.

O'Neil, D.A., Petty, M.D., 2013. Organizational simulation for model based systems engineering. Procedia Comput. Sci. 16, 323–332. https://doi.org/10.1016/j.procs.2013.01.034.

Ouchon, P.B., Aguilera, J.M., Pyle, D.L., 2003. Structure oil-absorption relationships during deep-fat frying. J. Food Sci. 68, 2711–2716. https://doi.org/10.1111/j.1365-2621.2003.tb05793.x.

Panait, L., Luke, S., 2005. Cooperative multi-agent learning: the state of the art. Aut. Agents Multi-Agent Syst. 11, 387–434. https://doi.org/10.1007/s10458-005-2631-2.

Phinney, D.M., Frelka, J.C., Heldman, D.R., 2017. Composition-based prediction of temperature-dependent thermophysical food properties: reevaluating component groups and prediction models. J. Food Sci. 82, 6–15. https://doi.org/10.1111/1750-3841.13564.

Rask, C., 1989. Thermal properties of dough and bakery products: a review of published data. J. Food Eng. 9, 167–193. https://doi.org/10.1016/0260-8774(89)90039-3.

Sanz-Serrano, F., Sagues, C., Feyissa, A.H., Adler-Nissen, J., Llorente, S., 2017. Modeling of pancake frying with non-uniform heating source applied to domestic cookers. J. Food Eng. 195, 114–127. https://doi.org/10.1016/j.jfoodeng.2016.09.027.

Taherian, M., Mousavi, S.M., Chamani, H., 2018. An agent-based simulation with NetLogo platform to evaluate forward osmosis process (PRO Mode). Chin. J. Chem. Eng. 26, 2487–2494. https://doi.org/10.1016/j.cjche.2018.01.032.

Tan, K.J., Mittal, G.S., 2006. Physicochemical properties changes of donuts during vacuum frying. Int. J. Food Prop. 9, 85–98. https://doi.org/10.1080/10942910500473947.

Thorvaldsson, K., Janestad, H., 1999. A model for simultaneous heat, water and vapour diffusion. J. Food Eng. 40, 167–172. https://doi.org/10.1016/S0260-8774(99)00052-7.

van Koerten, K.N., Schutyser, M.A.I., Somsen, D., Boom, R.M., 2015. A pore inactivation model for describing oil uptake of French fries during pre-frying. J. Food Eng. 146, 92–98. https://doi.org/10.1016/j.jfoodeng.2014.09.010.

Vélez-Ruiz, J.F., Sosa-Morales, M.E., 2003. Evaluation of physical properties of dough of donuts during deep-fat frying at different temperatures. Int. J. Food Prop. 6, 341–353. https://doi.org/10.1081/JFP-120017813.

Vries, U.d., Sluimer, P., Bloksma, A., 1988. A quantitative model for heat transport in dough and crumb during baking. In: Cereal Science and Technology. Ystad, Sweden, pp. 174–188.

Wagner, M.J., Lucas, T., Le Ray, D., Trystram, G., 2007. Water transport in bread during baking. J. Food Eng. 78, 1167–1173. https://doi.org/10.1016/j.jfoodeng.2005.12.029.

Zandi, M., Dardmeh, N., Pirsa, S., Almasi, H., 2017. Identification of Cardamom encapsulated Alginate–whey protein concentrates microcapsule release kinetics and mechanism during storage, Stew process and oral consumption. J. Food Process. Eng. 40 https://doi.org/10.1111/jfpe.12314.

Zandi, M., Mohebbi, M., 2015. An agent-based simulation of a release process for encapsulated flavour using the NetLogo platform. Flavour Fragrance J. 30, 224–229. https://doi.org/10.1002/ffj.3234.

Zhang, J., Datta, A.K., Mukherjee, S., 2005. Transport processes and large deformation during baking of bread. AIChE J. 51, 2569–2580. https://doi.org/10.1002/aic.10518.

Zhang, T., Li, J., Ding, Z., Fan, L., 2016. Effects of initial moisture content on the oil absorption behavior of potato chips during frying process. Food Bioprocess Technol. 9, 331–340. https://doi.org/10.1007/s11947-015-1625-6.

Ziaiifar, A.M., Heyd, B., Courtois, F., 2009. Investigation of effective thermal conductivity kinetics of crust and core regions of potato during deep-fat frying using a modified Lees method. J. Food Eng. 95, 373–378. https://doi.org/10.1016/j.jfoodeng.2009.05.015.