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Determination of Mass Transfer Parameters During Deep Fat Frying of Rice Crackers

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Abstract: The accuracy of the knowledge of mass transfer parameters (effective moisture diffusivity, mass transfer Biot number and mass transfer coefficient) in the case of frying food, is essential and important for designing, modeling and process optimization. This study is undertaken to develop an approach for determining mass transfer parameters during frying of spherical rice cracker in sunflower oil at 150, 170 and 190 °C. These parameters were evaluated from the plots of dimensionless concentration ratios against time of frying. Effective moisture diffusivity, mass transfer Biot number and mass transfer coefficient ranged between 1.24×10^{-8} to 2.36×10^{-8} m^2/s, 1.96 to 2.34 and 5.51×10^{-6} to 9.70×10^{-6} m/s, respectively. Effective moisture diffusivity and mass transfer coefficient were found to increase with an increasing frying temperature, whereas mass transfer Biot number decreased. An Arrhenius-type relationship was found between effective diffusivity coefficient and frying temperature.
Key words: frying; rice cracker; effective moisture diffusivity; mass transfer Biot number; mass transfer coefficient

Rice is one of the most important staple food, which is popular all over the world. About 90% of its production and consumption is reported in Asia (Ghasemi et al, 2009). The most production of rice is in China, with an annual production of about 194 million tones. Other Asian countries such as India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, the Philippines and Japan are the principal rice producers in the world (FAO, 2008). More than 2.8 million tones of rice is produced annually in Iran (FAO, 2008), and it is also used as the main ingredient of much Iranian food (some of traditional Iranian rice-based food are Halwa, Coofteh, Digcheh, Ashe Berenj and Shirberenj). Many research articles on rice cooking, quality and nutritional properties have been published (Dong et al, 2007; Liu et al, 2009). Rice can be also utilized in a vast range of food products such as rice crackers, rice flour, breakfast cereals, rice condiments, crisped rice and puffed rice (Sun et al, 2009). Rice cracker is one of the most favorite snack food in several Asian countries such as Japan, Thailand, Vietnam, Malaysia and Indonesia. Deep fat frying is one of steps in the production of rice crackers (Maneerote et al, 2009). Deep fat frying also called immersion frying, which can be used for production of food with desirable characteristics such as smooth mouth feel, distinct flavor, color, texture and palatability (Adedeji et al, 2009). In this process, the food is cooked by immersing in hot edible oil with the oil temperature usually at 150−200 °C (Farinu and Baik, 2008). Design, control and optimization of a frying process must be efficient, safe and economical. For this reason, modeling of frying process and determination of accurate heat and mass transfer parameters during frying are very important (YildIz et al, 2007). There are three methods for measuring the convective heat transfer coefficients: (1) steady-state measurement of surface temperature, (2) transient measurement of temperature, and (3) heat flux measurement of surface temperature (Alvis et al, 2009). Several studies on determination of convective heat transfer coefficients during frying of food have been reported. Heat transfer coefficients during sweet potato frying were determined by Farinu and Baik (2007). Hubbard and Farkas (2000) determined the heat transfer coefficients by convection during frying of potato cylinders and reported the values of heat transfer coefficients of 610, 650 and 890 $W/(m^2\cdot K)$ at 120, 150 and 180 °C, respectively. Potato slices (8.5 mm × 8.5 mm × 70.0 mm) were fried in sunflower oil at 150−190 °C by Yildiz et al (2007) and the heat transfer coefficients were determined. Costa et al (1999) used a steel piece with the same geometry of one English potato and obtained the values of heat transfer coefficients between (594 ± 38) and (750 ± 59) $W/(m^2\cdot K)$, and for French fries found values (h) between (443 ± 32) and (650 ± 7) $W/(m^2\cdot K)$ at temperatures of 140 and 180 °C, respectively. In addition to heat transfer coefficients, determination of mass transfer parameters is very

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important for modeling and analysis of frying processes. Mass transfer parameters are useful and vital in understanding the dynamics of the process and predicting the rate of mass transfer during deep-fat frying (Farinu and Baik, 2008). In general, three types of mass transfer occur in food during deep-fat frying: (1) moisture transfer from the center of food towards the surface, (2) edible oil transfer in the form of absorption from fryer environment into the food, and (3) liquefied components transfer in the form of leaching from the food towards the fryer environment (Debnath et al, 2009). Farinu and Baik (2008) determined the mass transfer coefficients from finite element simulation during deep-fat frying of sweet potato. Yildiz et al (2007) obtained the values of mass transfer coefficients between $(1.12 \pm 0.22)\times10^{-5}$ and $(2.07 \pm 0.24)\times10^{-5}$ m/s during deep-fat frying of potato slices. They also found the values of effective moisture diffusivity of $(9.2 \pm 1.1)\times10^{-9}$ and $(18.2 \pm 0.7)\times10^{-9}$ m^2/s at temperatures of 150 and 190 °C, respectively. We used an unpublished work for frying of cylindrical potato, determined the range of effective diffusivity coefficients from 8.93×10^{-9} to 18.63×10^{-9} m^2/s. In spite of h, there is not enough research on mass transfer parameters during deep-fat frying of food products. The object of this study is to determine mass transfer parameters (convective mass transfer coefficient, effective moisture diffusivity and mass transfer Biot number) during deep-fat frying of spherical rice cracker slices.

MATERIALS AND METHODS

Materials

Glutinous rice was purchased from a local market in Iran and kept at 25 °C prior to processing. Fish powder was also purchased and stored in polyethylene bags in a refrigerator at 4 °C. Sunflower liquid oil (Shadgol Company, Iran) was used as the frying oil. Frying was done at 150, 170 and 190 °C, respectively.

Rice cracker preparation

Momiyama (1981) has described the method for making a rice cracker in details. In this study, rice crackers were prepared by soaking milled glutinous rice in 20 °C water for 16−18 h. The drained rice was crushed by double rollers into fine powder and steamed in a pressure cooker at 115 °C for 12−13 min. After steaming, the resulting dough was kneaded two times and mixed with two levels of fish powder (0 or 200 g/kg total weight basis) by a screw kneader until a homogeneous mixture was obtained. The kneaded cake was placed in a cake vessel and cooled for 2−3 d at 2−4 °C for hardening the texture (Maneerote et al, 2009). The hard cake was cut into spherical pieces (1 cm in diameter) by using a metal mould and a knife. After that, the small pieces of hard cake were dried by hot air at 50−60 °C to obtain the final moisture content of 180 g/kg (wet basis) prior to frying.

Deep-fat frying method

A domestic deep-fryer (Techno Company, Te-500 model, Iran) was used. Spherical pieces of rice cracker immersed into the frying medium and fried for different time intervals at 150, 170 and 190 °C. Fried rice cracker samples were sampled at 20, 40 and 60 s, and up to 420, 360 and 280 s at 20 s interval of the frying process at 150, 170 and 190 °C, respectively. Frying time duration for different temperatures were experimentally selected to obtain the moisture content of 60 g/kg (wet basis) in final product. Surface oil was removed with a paper towel immediately after removal of the samples from the deep-fryer (YildIz et al, 2007), and the moisture content of samples was determined by drying the samples to a constant weight at (105 ± 1) °C (AOAC, 1975). Time-moisture content data of the rice cracker samples at different time intervals were used in the mathematical method for determination of the mass transfer parameters.

Mathematical model development

The partial differential equation (PDE) of continuity for component A can be written in a general form as (Bird et al, 2001):

$$\frac{\delta C_{\mathrm{A}}}{\delta t} = D_{\mathrm{eff}} \nabla^2 C_{\mathrm{A}} + R_{\mathrm{A}} \tag{1}$$

Where C_{A}, D_{eff} and R_{A} are moisture content, effective moisture diffusivity and rate of production of component A by homogeneous chemical reaction, respectively. The equation (1) is known to diffusion equation and it can be utilized for description of water transport in solids. The general form of diffusion equation in spherical coordinate can be written as:

$$\begin{aligned}&(\frac{\partial C_{\mathrm{A}}}{\partial t} + u_r \frac{\partial C_{\mathrm{A}}}{\partial r} + \frac{u_\theta}{r} \times \frac{\partial C_{\mathrm{A}}}{\partial \theta} + \frac{u_\varphi}{r \sin\theta} \times \frac{\partial C_{\mathrm{A}}}{\partial \varphi}) = \\ &D_{\mathrm{eff}}[\frac{1}{r^2} \times \frac{\partial}{\partial r}(r^2 \frac{\partial C_{\mathrm{A}}}{\partial r}) + \frac{1}{r^2 \sin\theta} \times \frac{\partial}{\partial \theta}(\sin\theta \frac{\partial C_{\mathrm{A}}}{\partial \theta}) + \\ &\frac{1}{r^2 \sin^2\theta} \times \frac{\partial^2 C_{\mathrm{A}}}{\partial \varphi^2}] + R_{\mathrm{A}}\end{aligned} \tag{2}$$

The diffusion equation can be simplified and analytically solved under the following assumptions: 1) The initial moisture distribution is uniform; 2) The effective moisture diffusivity is constant; 3) The convective mass transfer coefficients do not vary during diffusion; 4) The rate of production of species A by homogeneous chemical reaction is immaterial; 5) The dimensions of the solid do not vary during diffusion; 6) Liquid diffusion is the only transport mechanism of water inside the solid; 7) The solid is homogeneous; 8) The concentration gradients in the directions of the θ-and ϕ-axes are neglectible; 9) The velocity of system in all directions is zero.

After applying the above hypotheses on the diffusion equation, Eq. (2) can be simplified as:

$$\frac{\partial C_{\mathrm{A}}}{\partial t} = D_{\mathrm{eff}}[\frac{1}{r^2} \times \frac{\partial}{\partial r}(r^2 \times \frac{\partial C_{\mathrm{A}}}{\partial r})] \quad (3)$$

The Eq. (3) gives the concentration as a function of time and location for a spherical solid. The required initial condition (I.C) and boundary conditions (B.C) for solution of partial differential equation are given at Eq. (4) to Eq. (6).

$$I.C \rightarrow C_{\mathrm{A}}(r,0) = C_{\mathrm{i}} \quad (4)$$

$$B.C(1) \rightarrow C_{\mathrm{A}}(0,t) = \mathit{finite} \quad (5)$$

$$B.C(2) \rightarrow -D_{\mathrm{eff}} \frac{\partial C_{\mathrm{A}}(r_0,t)}{\partial r} = k_{\mathrm{C}}(C_{\mathrm{A}}(r_0,t) - C_{\infty}) \quad (6)$$

Where $C_{\mathrm{A}}(r;\ t)$, C_{i}, k_{c}, r_0 and C_{∞} are moisture content at any point any time (kg/kg solids), initial uniform moisture content of rice cracker (kg/kg solids), effective mass transfer coefficient (m/s), spherical rice cracker radius (m), and moisture content of frying medium (0 kg/kg solids), respectively. The convective boundary condition (Eq. (6)), also called boundary condition of the third kind or still Cauchy boundary condition. The solution $C_{\mathrm{A}}(r;\ t)$ of Eq. (3) for a homogeneous sphere with uniform initial moisture content C_{i} and boundary conditions defined by Eq. (5) and Eq. (6) can be obtained by separation of variables:

$$C(r,t) = \sum_{n=1}^{\infty} C_n \sqrt{\frac{2}{\pi\lambda_n}} r^{-1} \sin(r\lambda_n) \mathrm{e}^{-D_{\mathrm{eff}}\lambda_n^2 t} \quad (7)$$

Where C_n is defined by the following equation:

$$C_n = \sqrt{\frac{\pi\lambda_n}{2}}(C_{\mathrm{i}} - C_{\infty}) \frac{(\frac{\sin(r_0\lambda_n)}{\lambda_n^2} - \frac{r_0\cos(r_0\lambda_n)}{\lambda_n})}{(\frac{r_0}{2} - \frac{\sin(2r_0\lambda_n)}{4\lambda_n})} \quad (8)$$

λ_n is the root of the characteristic equation for a spherical solid, given by:

$$1 - r_0\lambda_n \cot(r_0\lambda_n) = \frac{k_{\mathrm{C}} r_0}{D_{\mathrm{eff}}} \quad (9)$$

For the values of $D_{\mathrm{eff}}t/r_0^2$ are greater than 0.1, using only the first term of Eq. (7) provides sufficiently accurate results (Crank, 1975). Therefore, it is obtained:

$$\frac{C_{\mathrm{A}}(r,t) - C_{\infty}}{C_{\mathrm{i}} - C_{\infty}} = \frac{\frac{\sin(r_0\lambda_1)}{\lambda_1^2} - \frac{r_0\cos(r_0\lambda_1)}{\lambda_1}}{\frac{r_0}{2} - \frac{\sin(2r_0\lambda_1)}{4\lambda_1}} \times \frac{\sin(r\lambda_1)}{r} \mathrm{e}^{-D_{\mathrm{eff}}\lambda_1^2 t} \quad (10)$$

The average moisture content at time t is given by:

$$\overline{C}(t) = \frac{1}{V}\int_0^V C_{\mathrm{A}}(r,t)dV \quad (11)$$

Where V is the volume of the sphere. By integrating $C_{\mathrm{A}}(r;\ t)$ throughout the whole volume, the equation for average moisture content ($\overline{C}(t)$) in a spherical solid is obtained:

$$\frac{\overline{C}(t) - C_{\infty}}{C_{\mathrm{i}} - C_{\infty}} = \frac{6(\sin(r_0\lambda_1) - r_0\lambda_1\cos(r_0\lambda_1))^2}{(r_0\lambda_1)^3(r_0\lambda_1 - \sin(r_0\lambda_1)\cos(r_0\lambda_1))} \mathrm{e}^{-D_{\mathrm{eff}}\lambda_1^2 t} \quad (12)$$

Or in a simple form:

$$\frac{\overline{C}(t) - C_{\infty}}{C_{\mathrm{i}} - C_{\infty}} = \beta \mathrm{e}^{-D_{\mathrm{eff}}\lambda_1^2 t} \quad (13)$$

Where β is defined as follows:

$$\beta = \frac{6(\sin(r_0\lambda_1) - r_0\lambda_1\cos(r_0\lambda_1))^2}{(r_0\lambda_1)^3(r_0\lambda_1 - \sin(r_0\lambda_1)\cos(r_0\lambda_1))} \quad (14)$$

After taking the natural logarithm of both sides of Eq. (13), a linear equation is taken as the following form:

$$\mathrm{Ln}(\frac{\overline{C}(t) - C_{\infty}}{C_{\mathrm{i}} - C_{\infty}}) = \mathrm{Ln}\beta - D_{\mathrm{eff}}\lambda_1^2 t \quad (15)$$

When $\mathrm{Ln}(\frac{\overline{C}(t) - C_{\infty}}{C_{\mathrm{i}} - C_{\infty}})$ is plotted against time, the intercept and the slope of this linear graph are equated to $\mathrm{Ln}\beta$ and $-D_{\mathrm{eff}}\lambda_1^2$, respectively. The effective moisture diffusivity (D_{eff}) was determined in two steps. In the first step, from the intercept of $\mathrm{Ln}(\frac{\overline{C}(t) - C_{\infty}}{C_{\mathrm{i}} - C_{\infty}}) - t$ plot, β was obtained from the Eq. (14), the first root of the characteristic equation (λ_1) was calculated. In the next step, from the slope of the same plot, the effective moisture diffusivity was determined. In the following, dimensionless mass transfer Biot number (Bi) and mass transfer coefficient (k_{c}) were obtained from the Eq. (9).

$$Bi = 1 - r_0\lambda_n \cot(r_0\lambda_n) = \frac{k_{\mathrm{C}} r_0}{D_{\mathrm{eff}}} \quad (16)$$

RESULTS AND DISCUSSION

Fig. 1. showed the dimensionless concentration ratio against time at different frying temperatures (150, 170

and 190 °C). The intercept of these plots equaled to Lnβ. After determining the root of the characteristic equation (λ_1) from Eq. (14), the effective moisture diffusivity (D_{eff}) is determined from the slopes ($-D_{\text{eff}}\lambda_1^2$) of these plots at different temperatures. Higher frying temperatures resulted in a greater slope, and therefore the greater water loss rate.

The experimental data at the beginning of the rice cracker frying were not used in determining the effective moisture diffusivity, because at the beginning of the process, even greater slopes were observed as a result of the sudden loss of free surface moisture. Therefore, the linear sections of these points were presented in Fig. 1 and were used in determining the values of D_{eff}. After that, the mass transfer Biot number (Bi) and mass transfer coefficient (k_c) were obtained from the Eq. (16). The obtained values of D_{eff} varied from 1.24×10^{-8} to 2.36×10^{-8} m^2/s and 1.27×10^{-8} to 2.34×10^{-8} m^2/s at the temperatures ranged from 150 °C to 190 °C for rice crackers with and without fish powder, respectively (Table 1).

The effect of temperature on D_{eff} is generally described using Arrhenius type of relationship to obtain better agreement of the predicted curve with experimental data (Eq. (17)).

$$D_{\text{eff}} = D_0 e^{-\frac{E_a}{RT}} \tag{17}$$

Where E_a is the activation energy and D_0 is the Arrhenius constant (m^2/s). After taking the natural logarithm of both sides of Eq. (17), a linear equation is taken as the following form:

$$\text{Ln}(D_{\text{eff}}) = \text{Ln}(D_0) - \frac{E_a}{R}\left(\frac{1}{T}\right) \tag{18}$$

When Ln(D_{eff}) is plotted against ($1/T$), the intercept and the slope of this linear graph are equated to Ln(D_0) and (E_a/R), respectively (Fig. 2). The values of D_0 and E_a by using of curve fitting toolbox (cftool) in MATLAB software were obtained. Therefore, the temperature dependence of effective moisture diffusivity is presented by following equations:

Rice crackers with fish powder:

$$D_{\text{eff}} = 1.9211\times10^{-5} e^{-\frac{3116}{T}} \tag{19}$$

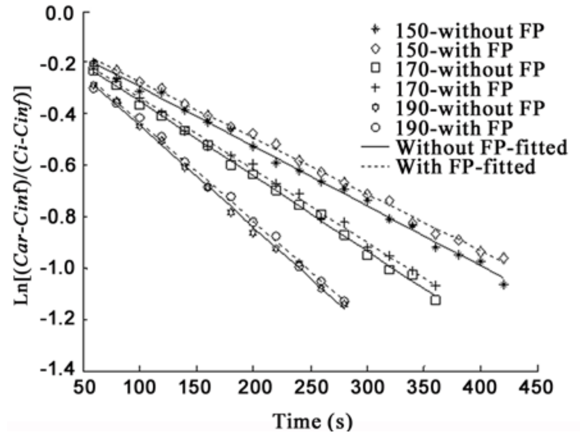

Fig. 1. Dimensionless concentration ratio-time plots at different temperatures.

With FP, The rice cracker with fish powder; Without FP, The rice cracker without fish powder; 150, 170 and 190 refer to the temperatures of 150, 170 and 190 °C.

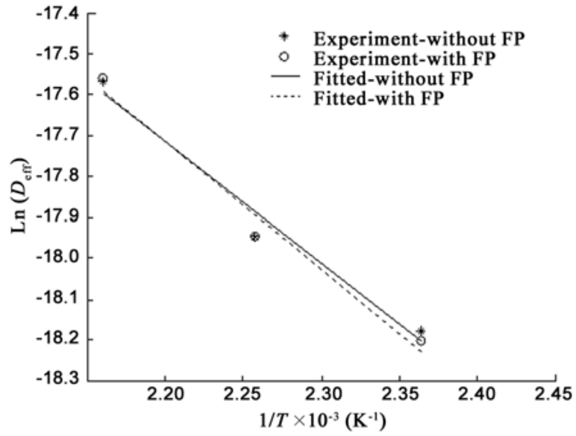

Fig. 2. Effective moisture diffusivity-temperature dependency.

With FP, The rice cracker with fish powder; Without FP, The rice cracker without fish powder.

Rice crackers without fish powder:

$$D_{\text{eff}} = 1.3811\times10^{-5} e^{-\frac{2966}{T}} \tag{20}$$

The experiment results are consistent with findings reported by other authors (McMinn and Magee, 1996; Kashaninejad et al, 2007; YildIz et al, 2007). The values of these parameters are presented in Table 1. As is shown, k_c increased with the increasing frying temperature. Fig. 3 confirms this finding and Eq. (21)

Table 1. Mass transfer parameters (mass transfer Biot number, mass transfer coefficient and effective moisture diffusivity) at different frying temperatures.

Frying temperature (°C)	With fish powder			Without fish powder		
	Mass transfer Biot number (Bi_m)	Mass transfer coefficient (m/s) ($k_c\times10^{-6}$)	Effective moisture diffusivity (m^2/s) ($D_{\text{eff}}\times10^{-8}$)	Mass transfer Biot number (Bi_m)	Mass transfer coefficient (m/s) ($k_c\times10^{-6}$)	Effective moisture diffusivity (m^2/s) ($D_{\text{eff}}\times10^{-8}$)
150	2.21	5.51	1.24	2.34	5.98	1.27
170	2.19	7.06	1.60	2.32	7.46	1.61
190	1.96	9.31	2.36	2.06	9.70	2.36

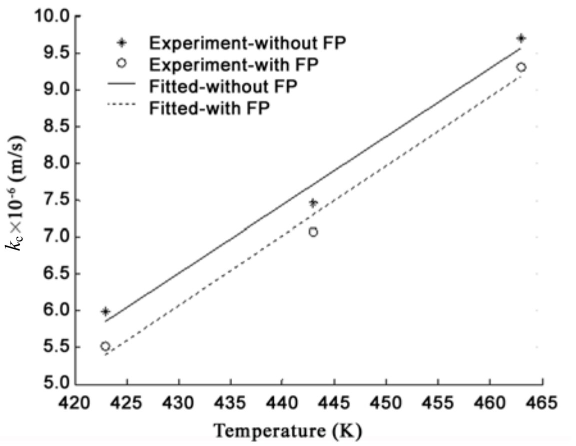

Fig. 3. Mass transfer coefficient-temperature dependency.

With FP, The rice cracker with fish powder; Without FP, The rice cracker without fish powder.

and Eq. (22) predict the temperature dependency of the k_c by a linear relationship:

Rice crackers with fish powder:

$$k_C = 9.48 \times 10^{-8} T - 3.47 \times 10^{-5} \quad (21)$$

Rice crackers without fish powder:

$$k_C = 9.294 \times 10^{-8} T - 3.346 \times 10^{-5} \quad (22)$$

Mass transfer Biot number (Bi) is also related to temperature by a linear relationship in Eq. (23) and Eq. (24):

Rice crackers with fish powder:

$$Bi = -0.00617T + 4.861 \quad (23)$$

Rice crackers without fish powder:

$$Bi = -0.00701T + 5.351 \quad (24)$$

Activation energy, mass transfer Biot number and mass transfer coefficient fall within the range of values that were reported by other researchers (Bon et al, 1997; Park et al, 2002; Doymaz, 2004).

Glutinous rice is usually used to produce fried, baked or popped snacks because of its sticky nature. Due to lack of amylose in the starch, it can expand readily to produce a porous texture of finished product (Maneerote et al, 2009). Moreover, glutinous rice with different varieties, cultivating locations, has different physicochemical properties such as amylose content, alkali digestibility, and pasting behavior. Therefore, determination of product porosity and finding a model for prediction of mass transfer parameters might be depend on glutinous rice variety, which will be investigated in future work.

CONCLUSIONS

In this study, mass transfer parameters during deep fat frying of rice crackers were determined. The methodology for determination of mass transfer parameters was based on the measurement of time-dependent dimensionless moisture content of rice cracker. The values were comparable with those obtained by other researchers and for other fried products. Mass transfer coefficient (k_c) and mass transfer Biot number (Bi) had lineal relationships with the frying temperature. This study also showed that the temperature dependence of the effective moisture diffusivity was described satisfactorily by an Arrhenius type of relationship. Frying temperature is a significant factor in frying of rice cracker. Higher frying temperature resulted in a shorter frying time.

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