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ORIGINAL PAPER

The Effect of Methylcellulose, Temperature, and Microwave Pretreatment on Kinetic of Mass Transfer During Deep Fat Frying of Chicken Nuggets

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Abstract The aim of this study was to determine the effect of microwave pretreatment, usage of methylcellulose, oil temperature, and frying time on mass transfer during deep fat frying of chicken nuggets. Methylcellulose was used in batter and as a coating on product. Microwave with two power densities namely 3.7 and 7.4 W/g was used for reduction of initial moisture content of samples before frying. Frying was performed at three temperatures (150 °C, 170 °C, and 190 °C) and five intervals (0.5, 1, 2, 3, and 4 min) in the sunflower oil. The least oil content was observed when MC was used as a coating layer on non-precooked samples fried at 190 °C. Oil absorption of samples with MC in batter was partially higher compared to control samples. This could be attributed to the rheology of batters. The first-order kinetic model was fitted to moisture and oil content. For determining the correlation between temperature and moisture diffusivity, Arrhenius equation was used. The constant rate for moisture and oil transfer was in the range of 2.2–5 and 0.023–2.67 s^{-1}, respectively. Effective moisture diffusivity values were between 1.43×10^{-8} and 3.24×10^{-8} m^2/s. Activation energy ranged between 0.71 and 1.71 kJ/mol.

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Introduction

Chicken nugget is one of the desirable breaded fast food which is produced with application of deep fat frying operation. Frying is one of the oldest important cooking methods that dates back as early as 1600 BC. This preparation method has been widespread utilized at domestic and industrial scale because of its benefits such as savory flavor, particular color, and crispy texture of the fried products. Consumers like eating product with crispy surface but moistly and soft core. In such product, coating leads to improvement of flavor, appearance, and texture. Also the other main role of coating layer is reducing fat uptake because of dry external surface. Coating layer in some product may contain antioxidant, flavoring, or fat uptake reducer agent such as hydrocolloids.

Type of material, formulation, and viscosity of batter in the coating layer affect quality of fried foods. The most important quality attribute for fried foods is fat content because nowadays regarding changes in lifestyle and eating habits, consumers are interested in products with less fat contents. Thus, several approaches have been proposed for reducing fat absorption during frying. Pretreatments which reduce this parameter include preliminary drying (with microwave or air dryer or osmotic solution) of the product, usage of fat reducer agent such as hydrocolloids in batter or as a coating on the surface of product, and optimization of frying conditions (Fiszman and Salvador 2003; Adedeji et al. 2009).

Preliminary moisture content is the most important effective attribute of food material that influences oil uptake. High moisture content of food leads to an increase of moisture loss during frying and then produces more porous product that increase oil penetration (Sahin and Sumnu 2009). Adedeji et al. (2009) evaluated the effect of microwave precooking, time and temperature on mass transfer for coating, and core portion of chicken nuggets, and they reported that precooking at 6.7 W/g resulted in the production of chicken nuggets with the least fat uptake at all frying temperatures. Ngadi et al. (2009) successfully reduced fat uptake of chicken nuggets by reducing primal moisture content. They precooked samples in microwave with 14.1 W/g power density at 1 and 2 min and reported that increase of precooking time caused decrease of free moisture content thereupon decrease of oil uptake. Air drying pretreatment for reducing moisture content is the successful method for reducing oil uptake of potato products. Krokida et al. (2001b) studied predrying for improving quality of French fries specially. Decreasing oil absorption in potato strips during deep fat frying was studied by Rimac-Brncic et al. (2004). They investigated influence of oil origin and prefrying treatment on the oil absorption and reported 54% reduction in oil content for the potato strips blanched in 0.5% calcium chloride solution following immersion in 1% solution of carboxyl methylcellulose. The effect of osmotic solutions was investigated by Ikoko and Kuri (2007) on banana slices and Mai Tran et al. (2007) on potato strips.

Hydrocolloids are defined as water-soluble polymers that can confer viscosity or gelate aqueous system and are able to retain water in food system (Sahin and Sumnu 2009). Singthong and Thongkaew (2009) investigated influence of hydrocolloid (pectin, carboxyl methylcellulose (CMC), and alginate) on the oil uptake of banana chips during frying. They concluded that pectin was the most effective hydrocolloid for low fat fried banana chip production. Bertola et al. (2002) investigated the effect of cellulose derivatives on reducing oil uptake, and reported methylcellulose was more effective compared to hydroxypropyl methylcellulose (HPMC). Methylcellulose and other cellulose derivatives exhibit thermal gelation and form a structure upon heating. Thermogelation property of these hydrocolloids with their film-forming ability has meant that they have a widespread application such as their use in batter formulas or as edible coating for moisture retention and oil reduction in fried food. Many authors believe that MC is one of the best hydrocolloid for reducing oil uptake with a good efficiency in batter system or as a coated film on food materials (Gauri and Susanne 2002; Sanz et al. 2005; Salvador et al. 2008; Chen et al. 2008).

Deep fat frying can be defined as a process of cooking and drying of food through contact with hot oil (160–205 °C), and it involves simultaneous heat and mass transfer (Moreira 2002). In fact heat permeates to food from oil and cause to evaporate the internal moisture of foods. This phenomena result in formation of a capillary path and increasing of porosity in the fried food. Then pores invigorate and oil enters to internal parts of the food through these pores, after frying during cooling (Moreira 2002; Ballard 2003; Duran et al. 2007). This two transferring processes are correlated and have a linear relationship (Krokida et al. 2000a, 2001a) and progress with specific kinetic. Kinetic modeling could describe these changes and their intensity. Studies on kinetics of oil uptake in coated products with hydrocolloids and breaded products are scarce in literature although the dynamics of various pretreatment effects on other non-breaded products have been widely studied (Moyano and Pedreschi 2006). Adedeji et al. (2009) performed mass transfer modeling for precooked and non-precooked chicken nugget fried at 170–190 °C. Troncoso and Pedreschi (2009) determined the kinetics of water loss and oil uptake during frying of pretreated potato slices under vacuum and atmospheric pressure. Duran et al. (2007) also fitted appropriated models to oil content data for potato slices. Kinetic modeling is performed by applying appropriate models for moisture loss and oil uptake that can be explained below.

Fick's law was used widespread to describe kinetic of mass transfer during frying of product with slab shapes. Solution of this equation for moisture loss was presented by Crank (1975) and shown as:

$$\mathrm{MR} = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

$$\mathrm{MR} = \frac{8}{\Pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left[-(2n+1)^2 \frac{\Pi^2 D_{\mathrm{eff}} t}{l^2}\right] \tag{2}$$

where MR is the moisture ratio (dimensionless), M_e is equilibrium moisture content (grams per gram, db), M_0 is initial moisture content (grams per gram, db), D_{eff} is effective diffusivity (square meters per second), t is time (seconds), and L is the thickness of sample (meters). With assuming M_e is very small, above equation was simplified:

$$\mathrm{MR} = \frac{M}{M_0} = \frac{8}{\pi} \exp\left(-\frac{\pi^2 D_{\mathrm{eff}} t}{4L^2}\right) = \frac{8}{\pi} \exp(-kt) \tag{3}$$

where k is the rate constant (per second).

Following equation determines the correlation between rate constant and effective moisture diffusivity:

$$D_{\mathrm{eff}} = \frac{4KL^2}{\pi^2} \tag{4}$$

Activation energy was obtained from Arrhenius equation and determined temperature dependency of moisture diffusivity during deep fat frying of chicken nuggets.

$$D_{\mathrm{eff}} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{5}$$

where E_a is the activation energy (kilojoules per mole), R is the universal gas constant (0.0083143 kJ/mol K), D_0 is the effective diffusivity at high liquid concentration (square meters per second), and T is the absolute temperature (kelvin).

First-order kinetic model recommended by Krokida et al. (2000b) was used for fat uptake modeling.

$$F_c = C_0[1 - \exp(-kt)] \quad (6)$$

where F_c is the fat content (grams per gram, db) and C_0 is the equilibrium fat content (grams per gram, db).

The aim of this study was to evaluate the effect of methylcellulose (in batter and as a film on coating), microwave pretreatment, and frying temperature on kinetic of mass transfer during deep fat frying of chicken nuggets.

Materials and Methods

Materials

Fresh chicken breasts, onion, pure table salt (Dordaneh, Keyhan Chemie Co., Iran), pepper, wheat flour (Toos Parak, Iran), baking powder (Zamen, Etminan Hadaf Toos Co., Iran), and 100% pure sunflower oil (NINA, oil products of Iran, manufactured by FRICO in S.S.E.Z.) were purchased from local market. Special breading materials were supplied from Pars Beryanak Co., Iran. The hydrocolloid used in this study was methylcellulose (SIGMA M7140, Chemical Co., Germany), and the solvent for fat extraction was synthetic grade petroleum ether (Scharlau Chemie S.A. ET0090, Made in European Union).

Sample Preparation

In this research, chicken nuggets were prepared manually. The core portion of this kind of nuggets consists of 86% de-boned skinless chicken breast, 1% salt, 12.9% onion, and 0.1% pepper. At first, fresh chicken breasts were skinned with kitchen knife and then washed. After removal of washing water, chicken breasts were parted from bones with kitchen knife and were grinded by meat grinder (Panasonic, model MK-1500P, Matsushita Electric Industrial Co., Japan). Mixing with spices was performed manually to achieve equal mixture. Widening was carried out for obtaining equal thickness (0.5±0.1 cm) in the final product. Samples then were placed in freezer (−18 °C) for about 2 h before cutting. Cutting was performed by a stainless steel mold. The dimensions of this mold were 2.6 cm (width)×4.5 cm (length). Samples were immersed into the batter suspensions after preparation of batter and immediately coated with breading materials. The dimensions of the chicken nugget samples were about 5 cm (length)×3 cm (width)×0.8 cm (thickness; ±0.1 cm). Chicken nuggets were stored in the freezer at −18 °C until frying.

To determine the effect of hydrocolloid on the quality of final product, methylcellulose was used. Therefore, two different batter formulations and three types of nugget samples were prepared (as given below).

The batters were prepared by mixing the dry ingredients with water for 1 min (with a short resting phase after 30 s) with a mixer (Katomo, Model HA-3020, Japan) to ensure uniform mixing. Water temperature was 25±1 °C.

Batter formulations

(a) Batter without hydrocolloid: This batter formulation was composed of 3:5 wheat flour-to-water ratio. In addition, 0.5% baking powder was added to flour.
(b) Batter with hydrocolloid: This suspension consists of 9% flour, 0.1% baking powder, 0.9% MC, and 90% water. At first, methylcellulose was added to water, and this hydrocolloid suspension was placed in a cold store (10 °C) for 2 h for complete hydration of hydrocolloid. Then other ingredients were added and mixed.

Nugget samples with different coating layer included control sample in which batter without MC was used, samples with MC in batter, and samples with MC on coating in which control samples were coated with 2% MC suspension.

Microwave Precooking

Nugget is a breaded product with partially dry external surface and moistly internal core. So to achieve predrying treatment goal, it seems that it is not suitable to apply hot air drying for this purpose. Adedeji et al. (2009) successfully used microwave heating for reducing moisture of chicken nuggets. In another research, air drying was utilized for foods with moistly surface such as potato strips (Krokida et al. 2001b). Microwave heating is based on the transformation of alternating electromagnetic field energy into thermal energy by affecting the polar molecules of a material such as water in foods (Vadivambal and Jayas 2010). High initial moisture content of the chicken nuggets could allow quick heating in the microwave oven. Microwave heating has many advantages such as shorter treatment time, saving of energy, improving product uniformity, and uniform moisture loss (Ngadi et al. 2009; Amiryousefi et al. 2010). Nuggets were transferred to refrigeration environment (at 4 °C) to be equilibrated for 10 h. Thawed chicken nuggets were precooked in a calibrated kitchen microwave oven (2,450 MHz, Butane model MB245, Iran) at two microwave power densities, namely 3.7 and 7.4 W/g for 60 s. Three samples were placed in the system for each batch. These power densities of precooking were chosen based on a preliminary study.

Frying Conditions

Frying was carried out in a deep fat fryer (Delongi 1,800 W, model F17233, Italy). For each stage, nine samples were fried in 1.5 L of sunflower oil. The un-precooked and precooked chicken nuggets were fried for 0.5, 1, 2, 3, and 4 min at three temperatures (150 °C, 170 °C, and 190 °C). The oil was preheated for 45 min at these temperatures prior to frying. Chicken nuggets immediately were blotted with paper tissue after frying to remove surface oil.

Analyses

Analyses of Fried Sample

Moisture content (db) was determined by drying the fried samples in an oven (PAAT Model SH2006, Ariya Co., Iran) at 105 °C for 24 h (Adedeji et al. 2009). For fat content (db) measurement, fat extraction was carried out with petroleum ether using a Soxhlet Extractor (Labor Muszeripari Muvek, model 0E-801, Hungary). The dried samples removed from oven were ground in a grinder (Nassiunal, model M-G-376-N, Iran). Three grams of the samples was weighed into thimbles, and these thimbles were placed into the extractor (Adedeji et al. 2009).

Analysis of Batter

Batter pickup The amount of batter adhering to the sample during immersion was considered as the batter pickup and calculated as the weight of batter picked up by a nugget divided by the non-coated nugget weight and multiplied by 100 (Dogan et al. 2005). Each sample was immersed in the batter for about 4 s.

Flow behavior and time dependency of batters were investigated at 25±0.1 °C. The viscosity was measured using a rotational viscometer (Bohlin Model Visco 88, Bohlin Instrument, UK) equipped with a heating circulator (Julabo, model F12-MC, Julabo Labortecknik, Germany). According to the viscosity of dispersion, appropriate measuring bob and cup (C30) was used for viscosity measurement. The batter was allowed to equilibrate for 15 min prior to running system. The samples were sheared at a programmed rate increasing from 10 to 400 s^{-1}. All analyses were performed in triplicates.

Kinetic Modeling

For better use of appropriate models to justify transferring phenomena should be attending to the model suppositions. Assuming initial uniform moisture content, negligible shrinkage and other changes in thickness of samples, negligible change in temperature of oil during intern sample to fryer and that mass transfer took place from both sides of the nuggets, and also thickness of samples was so smaller compared to the other dimensions, infinite slab model was selected (Moreira 2002).

For modeling of moisture loss, moisture ratio (MR) was calculated for all moisture content data. These new data were fitted to the appropriate exponential model (Eq. 3). Natural logarithm of moisture ratio data was calculated, then negative of natural logarithm of MR depicted versus time. The slope of straight line was fitted to data is the rate constant of moisture loss. Effective moisture diffusivity (D_{eff}) was determined from the rate constant by using Eq. 4. The temperature dependency of the effective diffusivity coefficient for moisture is shown by the Arrhenius expression (Eq. 5). Three frying temperature and their particular effective diffusivity were fitted to this model by using SlideWrite software plus 2.0.

For modeling of fat uptake, oil content data were fitted to special model (Eq. 6) by using SlideWrite software plus 2.0. Constant rate (k) and equilibrium fat content (C_0) were obtained for all precooked and non-precooked chicken nugget samples.

Statistical Analysis

Statistical analysis was performed using factor completely randomized design in Mstat version 1.42 software. The level of statistical significance was determined at 95%. If significant difference was found, the treatments were compared by using Duncan's multiple comparison test.

Results and Discussion

Batter Attributes

Flow behavior of the batters was examined by changing the shear stress with shear rate. Change in batter apparent viscosity with shear rate at 25 °C for two batter formulations can be seen in Fig. 1. All batters were found to be non-Newtonian and could be modeled as power-law fluid:

$$\tau = k(\mathrm{d}u/\mathrm{d}y)^n \tag{7}$$

where τ is the shear strain, $\mathrm{d}u/\mathrm{d}y$ is the gradient of speeds or shear rate, k is the consistency index, and n is the flow behavior index. In all the applied shear rates, batter with MC was found to have a lower apparent viscosity compared to batter without MC. The equation parameters (k and n) for different batter formulations and the amounts of batter pickup by the chicken nuggets were different in coating layer (Table 1). Batter without MC was more pseudoplastic

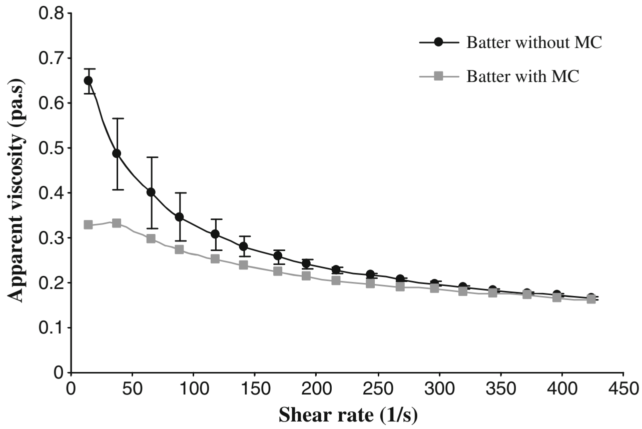

Fig. 1 Change in apparent viscosity with shear rate for two batter formulations

compared to batter with MC; this means increase of mixing shear rate caused more decrease in this batter's viscosity (Fig. 1). Batter pickup was higher when batter without MC was used. The deference between viscosities of these batters is the reason of deference in the batter pickup amount. Batter pickup was found to be directly proportional to batter viscosity. Amboon et al. (2010) investigated effect of HPMC on rheological behavior of batter based on rice flour and batter pickup. They reported that increase of viscosity in batter with HPMC caused an increase of pickup and moisture content of final samples, also decrease of oil content, and improvement of crispness of fried samples. Dogan et al. (2005) also observed similar correlation between viscosity of batter and batter pickup.

Effect of Temperature, Methylcellulose, and Microwave on Moisture Loss

Moisture loss could be considered as a function of frying time (Krokida et al. 2000b). In fact, moisture content decreased to achieve equilibrium content when frying was resumed. The water loss mechanism during frying is complex, and the transport by molecular diffusion, capillary, and pressure driven flow should be accounted (Pedreschi et al. 2007). In general, all food systems consist of different complex composite heterogeneous and anisotropic structures and are hygroscopic and capillary porous with definite void structures that modulate mass transport during heat processing (Kassama and Ngadi 2005). Analysis of variance demonstrated that the main effect of temperature, methylcellulose, microwave, and interactions between treatments were significant ($P<0.05$) on moisture loss (Table 2). As Fig. 2 shows, increasing frying temperature decreased moisture of sample and increased moisture loss rate. This similarly occurred for all samples precooked and un-precooked with microwave. The same trends were observed for all samples. Krokida et al. (2000b) achieved similar results in potato strips fried at the same temperature. In general, mass transfers is related to the development of microstructure and influenced by pore structure or distribution. High temperature increases the intensity of moisture migration and consequently induces reorganization of pores. Although it is known that high frying temperature changes pore structure in fried foods, but details is not well-known. New pores can be formed, whereas old pores can collapse during a heating process (Sahin and Sumnu 2009). This could be deducted that increase of temperature in this research influenced mass transfer through microstructure changes and intensified transport phenomena.

Increase of microwave power densities decreased primary moisture and certainly moisture content of final product decreased. The effect of microwave power density of 3.7 W/g was not significant on moisture loss.

Effect of hydrocolloid and its usage method on moisture content was significant. Moisture content of samples coated with MC suspension became maximum while it was minimum amount in control samples as it is depicted in Fig. 3. Singthong and Thongkaew (2009) found similar result on fried banana chips coated by hydrocolloids such as CMC, pectin, and sodium alginate. Sample with MC in batter was found to have a higher moisture content compared to control sample. This could be justified with difference in amount of water in their batters. Also, Fig. 3 shows that moisture loss amount for samples with MC in batter was higher than control samples. This could be correlated to the batter viscosity and pickup factors. In fact, decrease of batter viscosity and pickup in samples with MC in batter resulted in decrease of coating layer thickness, so higher amount of moisture were transferred in these samples during frying process.

Effect of Temperature, Methylcellulose, and Microwave on Fat Uptake

With resuming frying process, oil absorption increased to achieve equilibrium content. Figure 4 shows how the oil

Table 1 Consistency index (k, Pa s^n) and flow behavior index (n) and average values of batter pickup of different batters

Batter type	Parameter of power-law model			Batter pickup (%)
	k (Pa s^n)	n	R^2	
Batter without MC	1.4	0.6	0.95	41.0
Batter with MC	1.22	0.7	1.00	34.8

Table 2 Mean squares from the analysis of variance of the moisture content and fat content

Source	Degree of freedom	MC	FC
A	2	0.476*	0.001*
B	2	0.048*	0.075*
A×*B*	4	0.019*	0.001*
C	2	0.045*	0.013*
A×*C*	4	0.020*	0.002*
B×*C*	4	0.032*	0.002*
A×*B*×*C*	8	0.018*	0.001*
D	5	4.035*	0.179*
A×*D*	10	0.029*	0.003*
B×*D*	10	0.004 NS	0.003*
C×*D*	10	0.006 NS	0.001*
A×*B*×*D*	20	0.002 NS	0.000 NS
A×*C*×*D*	20	0.004 NS	0.000 NS
B×*C*×*D*	20	0.004 NS	0.001*
A×*B*×*C*×*D*	40	0.002 NS	0.001*
Error	324	0.004	0.000
Total	485		

MC moisture content, *FC* fat content, *A* temperature, *B* hydrocolloid, *C* microwave power, *D* time, *NS* not significant

*p=0.05

uptake during frying occurs. In fact, there was a sudden increase in oil content up to 50 s and then increasing process resumed very slowly. The results are in agreement with other studies (Duran et al. 2007; Adedeji et al. 2009; Troncoso and Pedreschi 2009). This behavior agrees with the hypothesis that surface wetting is a crucial mechanism for oil absorption. In fact, at first, moisture content of samples and their loss rate were higher. Because of moisture existing from food, porosity of samples increased. So oil was absorbed through these pores. But at the end of frying process, exiting of moisture from food decreased and surfacial pores were obstructed with oil. So porosity

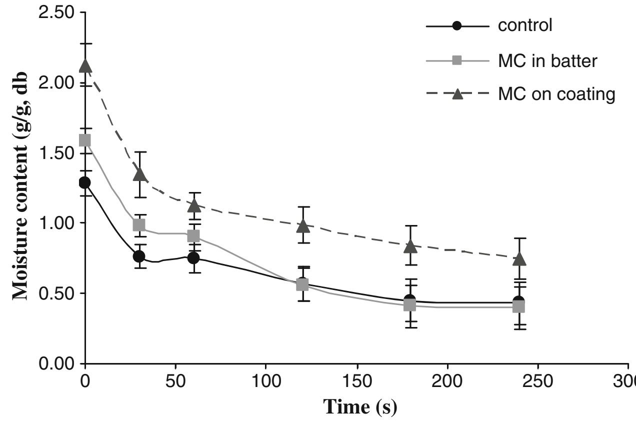

Fig. 3 Effect of hydrocolloid on moisture loss of un-precooked chicken nuggets fried at 190 °C

decreased and then caused decrease of oil absorption rate (Sahin and Sumnu 2009). Besides, these phenomena were dependent on the structural changes in fried foods such as denaturation of protein, forming of crust layer, and coagulation of starches (Adedeji et al. 2009).

Duncan's multiple comparison test shows that increase of frying temperature led to decrease in oil content in final product. This is depicted in Fig. 4 for un-precooked samples coated with MC. In fact, transferring and changes were performed rapidly in high temperature, but diagram became horizontal for short frying times and final product contained less oil content as samples fried at 190 °C had a lower fat uptake. Similar results were obtained for majority of the other samples types. Troncoso and Pedreschi (2009) obtained similar result for blanched and non-blanched potato slices fried at vacuum condition, 120 °C, and this was compared with atmospheric condition at 180 °C. Duran et al. (2007) reported similar result for potato chips fried in the range of 120 °C and 180 °C. Generally, at higher frying temperatures, crust layer forming and textural changes performed rapidly. Crust layer is a barrier for oil transport and prevents this mechanism during frying and after frying

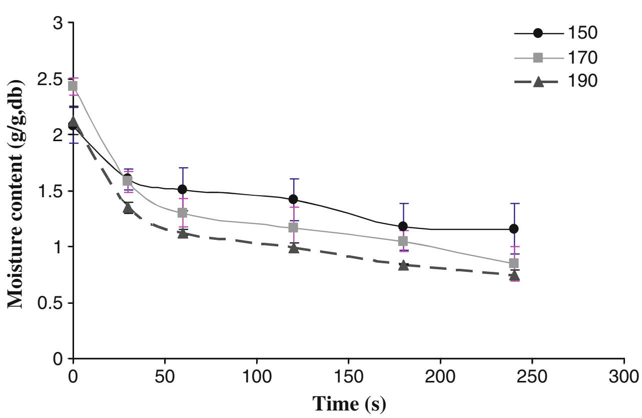

Fig. 2 Moisture loss as a function of frying temperature and time for un-precooked chicken nuggets coated with MC on coating

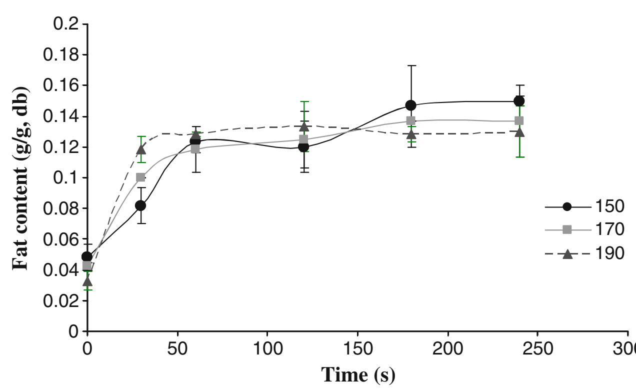

Fig. 4 Effect of frying time and temperature on oil uptake for un-precooked samples with MC on coating

during cooling (Moyano and Pedreschi 2006; Sahin and Sumnu 2009). Many authors believe that final fat content is not directly influenced by process temperature, but this is mostly correlated with moisture content and moisture loss (El-Dirani 2002; Moreira 2002). With attention to Figs. 2 and 4, it can be concluded that the highest oil uptake in each sample took place when maximum moisture was evaporated. Meanwhile, pore development caused penetration of oil to the food.

Methylcellulose had a significant effect on fat uptake. When methylcellulose was used as a film on coating, minimum fat uptake was obtained. Average of this parameter for control sample, sample with MC in batter, and sample with MC on coating were 0.132, 0.157, and 0.115 g/g, respectively, in dry basis. Rimac-Brncic et al. (2004) found that hydrocolloid usage as a coating film was able to decrease oil absorption for potato chips. Methylcellulose is water-soluble ether with good film-forming property that prevents fat transfer during frying.

With attention to difference of ingredient in two batter formulation, oil content of samples containing MC in batter was higher than control samples. This difference was observed in all un-precooked and precooked samples fried at all frying conditions and could be justified by difference in the viscosity of batter. Lower viscosity of batter with MC caused decrease in coating pickup parameter and coating layer thickness in samples with MC in batter (Table 1 and Fig. 5); thus, oil absorption of these samples was higher compared to control samples. Thicker coating layer prevents better transferring of moisture and fat during frying. So it could be deduced that oil absorption has a good correlation with batter viscosity and pickup of batter (Sahin and Sumnu 2009). Dogan et al. (2005) and Amboon et al. (2010) similarly found this correlation for different batter formulation.

Effect of microwave pretreatment on oil uptake was significant. Almost, for all samples, increase of power density caused to increase in oil content (Fig. 6). This could

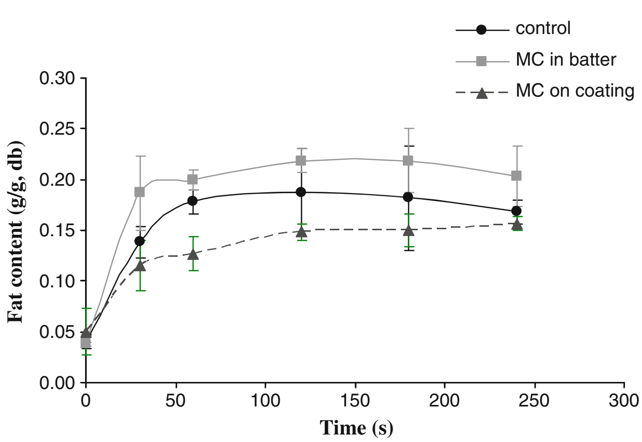

Fig. 5 Effect of hydrocolloid on oil uptake in precooked samples at 7.4 W/g power densities fried at 170 °C

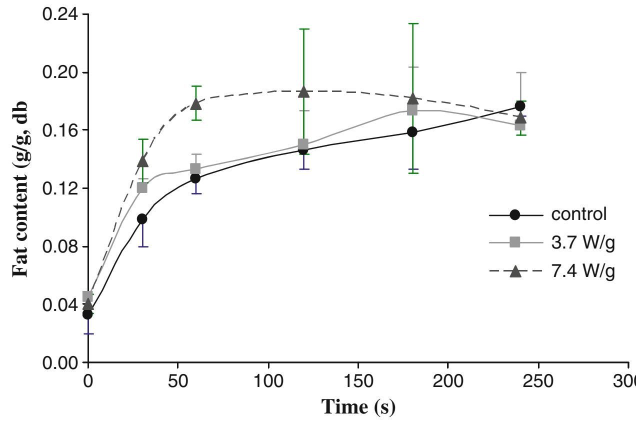

Fig. 6 Effect of microwave pretreatment on oil uptake for samples with MC on coating fried at 170 °C

be explained by increasing of porosity. Adedeji et al. (2009) similarly conclude that higher power densities cause increasing of oil content for breading part of chicken nuggets. But Krokida et al. (2001b) and Troncoso and Pedreschi (2009) reported that predrying by hot air before frying caused decrease of oil uptake in potato products. In fact in hot air dryer, heat transferring method is convection and moisture exit from surface of food material, at first. Hot air drying dehydrates the gelatinized starch in the surface of potato strips, creating an external crust which acts as an oil penetration barrier. But in this study, perhaps microwave with these power densities does not have a similar effect, and primary crust layer probably did not form on surface of chicken nugget before frying by microwave pretreatment. Thus, migration of moisture from food materials by this treatment and then increase of porosity became more important and helped transferring of oil.

Diffusion Modeling

Modeling of Moisture Loss

The model parameters for moisture diffusion in the samples are shown in Table 3. The effective moisture diffusivity of the samples ranged between 1.43×10^{-8} to 3.25×10^{-8} m^2/s. The coefficient of determination (R^2) ranged between 0.8 and 0.97.

Adedeji et al. (2009) reported these values in the range of 6.39×10^{-10} to 15.47×10^{-10} and 1.77×10^{-10} to 14.0×10^{-10} m^2/s for breading and core portion of chicken nugget, respectively, while Troncoso and Pedreschi (2009) found 8.57×10^{-9} to 2.95×10^{-8} m^2/s values for D_{eff} of pretreated potato slices. Parameter values in this study were slightly higher than the values reported by other authors.

Hydrocolloid as a coating layer decreased k and D_{eff} values. In most of nugget samples, microwave pretreatment caused partly decrease in these parameters. Krokida et al.

Table 3 Model parameters for moisture transfer in chicken nuggets were studied

Nugget sample type	Microwave power (W/g)	Temperature (°C)	$k\times10^{-3}$ (s^{-1})	$D_{eff}\times10^{-8}$ (m^2/s)	R^2
MC on coating	0	150	2.2	1.43	0.87
		170	3.7	2.40	0.85
		190	3.7	2.40	0.84
	3.7	150	2.6	1.69	0.88
		170	3.5	2.27	0.87
		190	3.7	2.40	0.81
	7.4	150	2.2	1.43	0.81
		170	3.2	2.08	0.89
		190	3.1	2.01	0.83
Control sample	0	150	3.3	2.14	0.89
		170	4.3	2.79	0.83
		190	4.3	2.79	0.83
	3.7	150	3.4	2.21	0.97
		170	3.7	2.40	0.88
		190	5.0	3.25	0.94
	7.4	150	2.9	1.88	0.84
		170	3.6	2.34	0.91
		190	3.2	2.08	0.80
MC in batter	0	150	3.1	2.01	0.90
		170	4.0	2.60	0.87
		190	4.8	3.12	0.88
	3.7	150	2.6	1.69	0.93
		170	3.7	2.40	0.93
		190	4.8	3.12	0.90
	7.4	150	3.1	2.01	0.84
		170	3.8	2.47	0.86
		190	4.7	3.05	0.82

0 W/g: un-precooked sample

(2001b) similarly reported that predrying of potato strips before frying caused decrease of effective moisture diffusivity. In general, removal initial moisture by these methods caused decrease of free moisture content of food materials and then decrease of moisture loss rate (Fig. 7). Moreover, using higher frying temperature increased these parameters. Significant differences on these parameters for samples coated with MC and other samples are depicted in Table 3. This can be justified with hydrocolloid's attributes; they prevent moisture and oil transports as a blockage.

Activation energy as a parameter of model and coefficient factor is shown in Table 4. The activation energy ranged between 0.71 and 1.71 kJ/mol. A range between 13.65 and 54.63 kJ/mol was presented by Adedeji et al. (2009) for moisture diffusion in breading part of chicken nuggets. Troncoso and Pedreschi (2009) reported this parameter between 23.5 and 29.3 kJ/mol for potato slices. The activation energy increased with microwave power density. In fact, decrease of free moisture content in precooked samples caused increase of energy necessary for exiting of remained moisture therefore moisture diffusivity decreased. Also samples with MC on coating had a higher amount of activation energy. This means that higher energy required for conquest of gel structure was created by hydrocolloid. In general, when treatments cause increase of activation energy,

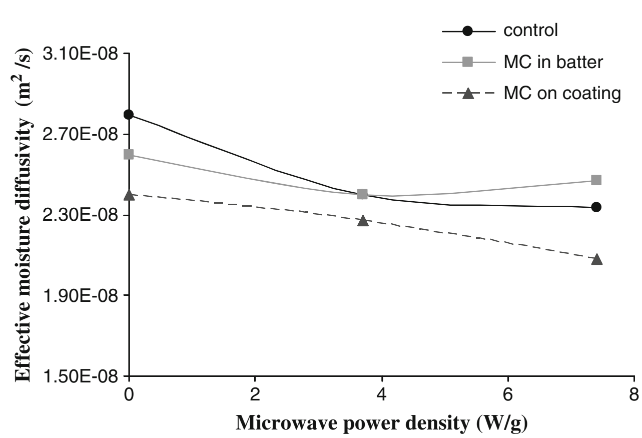

Fig. 7 Changes in D_{eff} values for three sample types fried in 170 °C, when microwave power density was increased

Table 4 Activation energy and R^2 values for precooked chicken nugget samples

Nugget sample type	M_w power (W/g)	E_a (kJ/mol)
Control	0	0.8
	3.7	1.51
	7.4	1.67
MC in batter	0	0.71
	3.7	0.74
	7.4	0.91
MC on coating	0	1.57
	3.7	1.67
	7.4	1.71

then lower moisture content could evaporate or transfer at the same condition and lower D_{eff} was obtained.

Modeling of Oil Uptake

Rate constant of fat uptake ranged between 0.023 and 2.67 s^{-1} with coefficient factor of 0.8–0.94 as shown in Table 4. Adedeji et al. (2009) reported rate constant in the range of 0.04–40.96 s^{-1} for breading coating of chicken nuggets fried at 170 °C, 180 °C, and 190 °C. Amiryousefi et al. (2010) reported k in the range of 0.024–19.708 s^{-1} for microwave pretreatment ostrich meat plates fried between 130 °C and 160 °C. Duran et al. (2007) presented a range of 0.185–2.001 s^{-1} for potato chips fried in 120–180 °C. Certainly, frying conditions, dimensions of samples (thickness specially), type of the product, and pretreatments are important parameters that determine fat absorption rate constants.

Increase of frying temperature resulted in increase of rate constant of fat absorption for all nugget samples. Microwave pretreatment caused increase of the rate constant of fat uptake, but differences were not significant. At temperature of 150 °C, usage of 7.4 W/g power density resulted in decrease of this parameter (Table 5). Adedeji et al. (2009) perceived that this pretreatment could result in a noticeable increase in the rate constants (0.04–40.96 s^{-1}).

Equilibrium fat content (C_0) is the other parameter in modeling of mass transfer during frying. In this study, increase of temperature decreased equilibrium fat content for all nugget samples types and minimum amount was observed in samples coated with MC (Table 5). In fact for true discussion about the effect of treatments on oil uptake, considering the rate constant is not enough. For example, about the effect of temperature, increase of this treatment caused an increase of constant rate, but this did not result in increase of oil uptake because equilibrium fat content decreased. Therefore, both two parameters are important for the best discussion.

Conclusion

Oil temperature, microwave pretreatment, and methylcellulose usage significantly affected mass transfer during deep frying. High temperature increased rate constant of moisture and fat transfer, but equilibrium fat content at higher temperature decreased. In this study, microwave precooking caused nearly increase of fat uptake. Study on other microwave power densities is recommended for more information about the effect of microwave on oil uptake. Also study on microstructural changes such as porosity and shrinkage changes during precooking and frying process, investigation on pore structure, and changes in crust layer could help us to clearly understand these phenomena.

In this study, the most reduction in oil content was achieved when methylcellulose was used as a coating layer

Table 5 Parameters of fat uptake model for chicken nuggets

Nugget samples	Temperature (°C)	Microwave power (W/g)					
		0		3.7		7.4	
		k	C_0	k	C_0	k	C_0
MC on coating	150	0.026 (0.85)	0.14	0.050 (0.85)	0.14	0.044 (0.83)	0.14
	170	0.041(0.89)	0.14	0.043 (0.91)	0.15	0.047 (0.87)	0.15
	190	0.085 (0.94)	0.13	0.066 (0.80)	0.12	0.104 (0.88)	0.12
Control	150	0.034 (0.87)	0.15	0.023 (0.81)	0.16	0.044 (0.88)	0.18
	170	0.027 (0.94)	0.17	0.040 (0.90)	0.16	0.520 (0.93)	0.18
	190	0.055 (0.88)	0.16	2.670 (0.90)	0.15	1.900 (0.90)	0.16
MC in batter	150	0.036 (0.88)	0.17	0.052 (0.86)	0.18	0.029 (0.93)	0.24
	170	0.060 (0.94)	0.17	0.062 (0.91)	0.18	0.074 (0.95)	0.21
	190	0.036 (0.93)	0.16	0.074 (0.90)	0.2	1.240 (0.91)	0.18

Numbers in parenthesis are coefficient of determination, R^2

on final samples. While methylcellulose was added to batter, the viscosity of batter was an important factor affecting fat absorption. In fact, batter viscosity had good correlation with batter pickup by nuggets. This factor affected fat transferring during frying and cooling. Kinetic modeling successfully could describe moisture and oil transports during frying of chicken nuggets. Increase of batter viscosity and usage of 2% methylcellulose suspension as a coating on product is recommended for reducing fat uptake during frying.

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