Modeling Moisture Diffusivity in Deboned Chicken Breast during Deep-Fat Frying

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Abstract

The effects of frying oil temperature on the effective moisture and oil diffusivities were investigated in this study. Samples of chicken meat were diced into 5 x 3 x 0.3 cm slabs. Liquid and vapor diffusivity were lumped and hence one-dimensional mass diffusion was assumed on an infinite slab. Chicken meat samples were fried at different temperatures (170, 180, and 190°C) in an industrial fryer for periods varying from 5 to 900 s. Fried samples were freeze-dried prior to fat analysis, hence moisture analysis was based on the AOAC standard methods. The effective moisture and oil diffusivities increased with frying oil temperature. Over the range 170 to 190ºC, the effective moisture diffusivity increased from 3.65E-09 to 7.42E-09, and the effective oil diffusivity increased from 9.12E-09 to 3.32E-08 m²/s, based on data from 5 to 900 s frying time. The activation energies were calculated to be 59.5 and 107 kJ/mol for moisture and oil diffusion, respectively.

Keywords: Diffusivity; Deep-Fat Frying; Oil Uptake; Moisture; Chicken Meat

Introduction

Deep-fat frying is a simultaneous heat and mass transfer process in which the food product with high initial moisture content is subjected to high heat treatment in oil as the medium of heat transfer [1-3]. During this process, heat is transferred to the product by the hot oil, resulting in vaporization of the product’s moisture. Heat is conducted through surface contact and as well as by penetration of the hot oil into the product via available pores. Hence, oil may also serve as an active ingredient for supplementary nutrients [4] and influences texture and sensory quality [5]. The parameters influencing the rate and efficiency of the frying process are oil temperature, product moisture content, frying time and physical characteristics of the product [1,2,4,6-9] and surface coatings [10-12].

Oil type and quality are also important to consider as these factors may also influence the physicochemical composition of the product. For example, additives and contaminants in oils can have a marked effect on the organoleptic attributes of the fried products [13] and modify the interfacial characteristic [6]. The characteristics of the food product, i.e. initial moisture content, shape and size, sample weight/frying oil volume and sample surface area/volume ratio, surface tension are factors that influence oil penetration and absorption. In consequence, the heat intensity may destroy the heat labile constituents and influence the interactions between nutrients in food and those in the frying oil [14].

Many authors associate frying to drying [7,15-17,8]. The drying process is divided into two distinct phases: the constant rate period and the falling rate period. The initial phase, when the surface moisture vaporizes into the cooking medium (oil) has been related to the constant rate period, which causes a considerable amount of turbulence due to boiling at the surface [17]. Throughout the falling rate period, the movement of moisture from the core to the drying surface occurs by diffusion and capillarity action. During this period the boiling front moves towards the internal core of the product. As a result, physicochemical changes such as
solubilization of proteins and denaturation of protein causes pore formation and pore collapse, and structural transformation such as shrinkage of the final fried product [2,6,7,19].

Kinetic modeling can elucidate the transport phenomena involved, and thereby complement the understanding of how the physical properties of the product may change at different combinations of the process variables. This may lead to optimization for a safer product. Several researchers have used kinetic modeling to describe desorption and absorption of moisture and oil, respectively, during deep-fat frying and other processes [7,15,20-23]. Kinetic modeling quantifies rate change, thus correlating the rate parameter to the physical changes that occur as the result of a process. The objective of this study is to determine the effect of frying temperature and time on effective moisture diffusivity and the rate constant of oil uptake in chicken breast slabs, and to develop an empirical model for fat absorption during deep-fat frying chicken breasts.

Moisture diffusion model

Mass diffusion from the chicken breast meat slab was modeled using governing equation of Fick’s second law of mass diffusion:

\[
\frac{\partial C}{\partial t} - D \frac{\partial^2 C}{\partial x^2} = 0
\]

Where \( C \) is the mass concentration of moisture or oil (kg/kg wb), \( t \) is the frying times, \( D \) is the effective diffusivity of the liquid in question (m²/s) and \( x \) is the thickness of the sample slab (m). In this study the resistance to moisture transfer at the surface, normally due to convective moisture transfer, was assumed to be negligible since water vapor was rapidly lost from the surface of the frying food. Furthermore, a one-dimensional mass diffusion was assumed on an infinite slab (i.e. the lateral dimensions are much greater than the thickness) of thickness \( l \) as shown in Eq (1).

The solution to Eq. 1 [24] is based on the following assumptions: uniform initial moisture content, negligible external resistance to moisture transfer. Many authors used Newman’s analytical procedure to obtain a solution for Eq 1, hence shown by Eq (2) the Newman solution

\[
x = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp \left( \frac{-(2n+1)^2 \pi^2 D_l t}{4l^2} \right)
\]

Where \( x \) is the mass content (moisture concentration), \( t \) is the frying time, \( l \) is the half thickness of the slab (m) and \( n \) is an integer associated to the sample population. Equation 2 was further simplified by assuming that the missing terms are relatively small. Thus, the expression (Eq 3) reduces to:

\[
x = \frac{8}{\pi^2} \exp \left( -\frac{\pi^2 D_l t}{l^2} \right)
\]

Materials and Methods

Samples used for the study were chicken breast. The chicken breast meat was acquired from a local chicken product manufacturer and was stored in a freezer at -20°C until used. Frozen samples were thawed in a refrigerator at 4°C for 24 to 36 h when needed. The samples were diced into approximately 5 cm (length) x 3 cm (width) x 0.3 cm (thickness) pieces. Sizing was difficult due to the irregular nature of chicken breast pieces, and, as a result, the length and width dimension may vary by approximately ±3 mm.

Frying

Frying was done in a commercial programmable computerized pressure deep-fat fryer Henny Penny Computron 7000 Pressure Fryer (Model 500C, Henny Penny Corporation, Eaton, OH), with a fat/oil holding capacity of about 30 L. A liquid shortening (Can Amera Food, Oakville, ON) was used. A sample to oil weight ratio of 1:480 was maintained, and samples were placed in a wire basket to ensure good contact between the sample and the oil. The fryer was preheated to 170°C for 2 h prior to frying. Samples were fried for a specific period of time, after which they were removed from the fryer, cooled at room temperature, weighed, placed in plastic Zip-Lock sample bags and frozen at −20°C in a freezer prior to further analysis.

Analytical methods

Moisture content

Procedure for the moisture analysis for the fried chicken samples was based on the prescribed method AOAC 960.42 [25]. Samples were place in an oven at 100°C for 18 h as stipulated in the recommended method. The initial mass of the samples prior to oven drying and the final mass of the dried product were determined using a TR-4102D scale (Denver Instrument Co., Denver, CO), hence the moisture content calculated.

Fat content

The freeze-dried fried samples were ground using a blender (Proctor-Silex, model E160B, Picton, ON). The ground samples (2-4 g) were weighed with an electronic scale (TR-4102D, Denver Instrument Co., Denver, CO) and placed in a thimble. Some sand was added to the sample in the thimble and mixed with a glass rod. Fat was extracted in a solvent extractor (SER148, Velp Scientific, Usmate, Italy) using petroleum ether. The mass of the glass extraction cups with a few boiling stones was recorded and 50 mL of petroleum ether was added to each cup. The thimbles were then inserted to the magnetic connector of the extraction unit. Procedure followed as recommended by AOAC Method 960.39 [26] and also (SER148, Operation manual). The thimbles were immersed in the boiling solvent for 30 min and then submitted to 60
min of reflux washing and 30 min of drying to recover the solvent. The extracts were further dried in a convection oven (Isotemp 700, Fisher Scientific, Pittsburgh, PA) at 125°C for 30 min. The sample cups were cooled in a desiccator and subsequently weighed. The oil content (OC) dry basis was computed for each sample using the following relationship: \[ \text{OC} \% = \frac{\text{mass of oil extracted}}{\text{mass of dried sample}} \times 100 \] (4)

Experimental design and statistical analysis

Frying times were randomized within each temperature and triplicates were run sequentially at each time [27]. There were three frying oil temperatures (170, 180, and 190°C), and 14 frying times (5, 10, 15, 20, 30, 45, 60, 90, 120, 150, 180, 210, 240 and 300). Initial fat content was determined on three samples (control). Regression analyses were conducted using SAS software (SAS v.8, Nashville). Duncan’s Multiple Range Test (DMRT) was used to separate treatment means (5% level of significance).

Results and Discussion

Moisture diffusivity

Experimental moisture content data was fitted as an exponential function of frying time according to Eq. 5: \[ x = ae^{-bt} \] (5)

Where \( a \) and \( b \) are constants. The values of \( a \) and \( b \) obtained at each temperature are given in Table 1. The rate constant \( b \) is associated to the moisture diffusivity by the following relationship:

\[ b = \frac{D_e}{\rho} \]

The rates of moisture loss were observed to be higher at high FOT. The temperature dependence of the rate constant is to be expected due to the energy considerations, similar information has also been reported in studies of fried potatoes [16,28] and deep-fried chicken drums [29] and chicken breast [1,2].

![Figure 1: Typical moisture history of chicken breast meat slab during deep-fat frying.](image)

Table 2: Effective moisture diffusivity values computed from the moisture desorption curve during deep-fat frying of chicken breast meat.

| Temperature (°C) | Effective Moisture Diffusivity (m²/s) | Std Deviation |
|------------------|---------------------------------------|--------------|
| 170              | 3.65E-09                              | 3.64E-10     |
| 180              | 5.23E-09                              | 5.57E-10     |
| 190              | 7.42E-09                              | 2.11E-10     |

Table 1: Estimated parameters of the moisture diffusion derived from equation 5 model during deep-fat frying of chicken breast.

| Temp (°C) | Model Parameters | |
|-----------|------------------|---|
|           | a (kg/kg wet basis) | b (s⁻¹) | R² |
| 170       | 0.81 | 0.0051 | 0.0010 | 0.0001 | 0.99 |
| 180       | 0.82 | 0.0085 | 0.0014 | 0.0001 | 0.98 |
| 190       | 0.84 | 0.0150 | 0.0020 | 0.0002 | 0.97 |

Temp = Frying temperature; SE = Standard error; R² = Coefficient of determination; \( a \) and \( b \) are the parameters in Eq. 5.

The observed moisture history at a frying oil temperature of 180°C is shown in Figure 1 along with the model predictions. The experimental model adequately described the data as indicated by the high R² and low variability of the parameter estimates (SE’s <11% of parameters). The moisture change with respect to time during deep-fat frying is analogous to that obtained in the dehydration of food products [30,31].

Figure 1: Typical moisture history of chicken breast meat slab during deep-fat frying.
in moisture diffusion especially at higher temperatures. The rapid increase in moisture loss from the denatured muscle as a result of FOT may have contributed to shrinkage, increased porosity and thus increased moisture diffusivity \[3,7,29,33,35\]. Another factor could be the loss of structural integrity of muscle myofibrils at temperatures above 97°C, hence at higher FOT would increase the rate of heat transfer thus may increase its rate deterioration.

The dependence of the effective moisture diffusion coefficient on temperature was assumed to follow the Arrhenius type model \(D_e = D e^{\left(\frac{aE_i}{RT}\right)}\).

Where \(D\) is the apparent diffusivity, \(E_i\) is the activation energy, \(R\) (8.314 J/K mol) is the universal gas constant, and temperature is absolute (K). The effective diffusivity is plotted against the inverse of temperature in Figure 2. The slope of the line is equals to the activation energy and the intercept is the apparent diffusivity. The ratio of the activation energy to the gas constant \(R\) is \(7275 /°K\), and the apparent moisture diffusivity as \(5E-07\) m²/s. The activation energy for effective moisture diffusivity was calculated to be 59.5 kJ/mol during DFF of chicken breast meat. Activation energies of 24 kJ/mol for DFF of chicken drums and 26 kJ/mol for deep-fried chicken nuggets were reported by El-Dirani \[10\], respectively. Motarjemi \[36\] reported activation energies ranging from 34 to 54 kJ/mol for moisture diffusion in mincemeat during oven frying. Low activation energy is an indication of greater ease of moisture transfer and is therefore dependent on the structure of the material and FOT.

### Table 3: The rate constants derived for oil uptake profile at different temperatures during deep-fat frying of chicken breast meat slab.

| Temperature (°C) | k (1 % Oil Uptake) | C₀ (s⁻¹) | R²  |
|------------------|--------------------|----------|-----|
| 170              | 8.13               | 0.0025   | 0.88|
| 180              | 10.85              | 0.0046   | 0.92|
| 190              | 9.99               | 0.0091   | 0.94|

The rate of oil absorption increases with increase in FOT. Figure 3 shows a typical experimental and predicted oil uptake history for samples fried for 180°C. The mathematical model seems to be well fitted to the experimental data as shown by the low standard errors.

### Table 4: The effective oil diffusivity values computed from the oil absorption curve during deep-fat frying of chicken breast meat.

| Temperature (°C) | Effective Oil Diffusivity (m²/s) | StdDeviation |
|------------------|----------------------------------|--------------|
| 170              | 9.12E-09                         | 1.70E-10     |
| 180              | 1.68E-08                         | 1.30E-09     |
| 190              | 3.32E-08                         | 2.3E-09      |

The effective oil diffusivities were computed based on Eq.7 and are shown in Table 4. The effect of frying oil temperature is significant (P<0.01) on oil diffusing into the chicken meat during deep-fat frying. The fact that moisture loss and oil uptake are positively correlated, it is an indication that oil diffusivity in chicken may be dependent on moisture diffusivity. The diffusion of oil during deep-fat frying is also dependent of the formation of capillary pores, which occurs as a result of moisture diffusion. The effective oil diffusivity is almost an order of magnitude greater than that of moisture diffusivity computed from the experimental data. This may be due to the fact that the moisture diffusivity involves two-phases (liquid and vapor), most of the moisture movement being due to diffusion of the vapor phase.
ent oil diffusivity was 7.0E-12 m²/s and the activation energy for oil absorption in chicken meat was found to be 107 kJ/mol.

Figure 4: The effective oil diffusivity curve obtained at different frying temperatures during deep-fat frying.

Moisture loss and oil uptake were found to be positively correlated through the first 360 to 420 s. Comparison of predicted oil uptake values using Eq.9 and the experimental values are shown in Table 5. Values predicted by the model were smaller (15 and 40%) than the actual experimental values for the FOT 180, and 190°C respectively. This discrepancy may have been due to the change in physical properties as a result of shrinkage. The effect of the erratic nature of oil uptake after 300 s of frying shown in Figure 3 may have induced some errors estimated by the model.

| Temperature | Oil Uptake |
|-------------|------------|
|             | Predicted  | Experimental |
| 170°C       | 4.66       | 4.28         |
| 180°C       | 7.06       | 8.14         |
| 190°C       | 9.34       | 10.04        |

Table 5: Comparison of predicted and observed oil uptake after 300 s frying at different FOT.

The relationship between moisture loss and oil uptake was positively correlated for up to about 360 s frying time. Therefore, it is possible to predict oil uptake from moisture loss using moisture diffusivity. Both parameters may be dependent on the physical properties of the food product being fried [1,2]. Pore formation due to moisture loss was elucidated by the capillary theory of drying [3,6,40]. The creation of capillary pathways enables oil uptake to occur [6,3,41]. However, it is apparent that increases in moisture diffusivity and pore formation will likely increase the rate of oil uptake.

Conclusions

Moisture loss and oil uptake are mass transfer phenomena that occur during deep-fat frying and are described by an empirical first order kinetic model. Based on the regression models, the effective moisture diffusivity was found to vary from 3.65E-09 to 7.42E-09 while the oil diffusivity ranged from 9.12E-09 to 3.32E-08 m²/s at temperatures ranging from 170 to 190°C, respectively, during deep fat frying of chicken breast meat slab for 900 s. The activation energy was calculated to be 59.5 and 107 kJ/mol for moisture and oil diffusion, respectively. Frying temperatures significantly (P < 0.01) affect moisture and oil diffusivity. The intensity of moisture loss and oil uptake increases with frying oil temperature. Better prediction of oil uptake was given during the first 300 s of frying. Change in the physical properties of the food product during deep-fat frying may have influenced the mass transport particularly after 300 s of deep-fat frying.

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