Indian Journal of Science and Technology, *Vol 11(6), DOI: 10.17485/ijst/2018/v11i6/117046,* February *2018*

ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645

Effect of Deep Fat Frying on the Mass Transfer and Color Changes of Arepa Con Huevo

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Abstract

Objectives: To study the effect of deep fat frying on the mass transfer and color changes of ArepaCon Huevo. **Methods:** The product was prepared as a round plate (diameter: 10 cm and thickness: 2.5 cm). Palm oil was used in a 7 L fryer at 170, 180 °C and 190°C under a ratio of 250 g sample/L oil. **Findings:** Moisture content decreased as time and temperature increased ($p<0.05$). Da coefficients in increased order of temperature were: (1.75 ± 0.01, 3.56 ± 0.08 and 5.03 ± 0.06 x10^{-7}) m^2/s, with k_c values of (4.26 ± 0.31, 6.31 ± 0.45 y 9.58 ± 0.81) m/s. The activation energy calculated with Arrhenius equation was 63.96 kJ/mol. The rate of oil absorption was higher at low temperatures, with values of (1.28 ± 0.06, 0.77 ± 0.02 and 0.67 ± 0.04 x 10^{-3}) s^{-1} and an activation energy of 50.66 kJ/mol. Lightness (L*) decreased with increasing factors, varying from 75.02 ± 3.42 (before frying) to 46.82 ± 2.28 at 190 °C. This was attributed to the non-enzymatic browning at high temperatures. **Application:** Understand mass transfer parameter is important in order to optimize the frying processing of ArepaCon Huevo.

Keywords: Arepa con huevo, Deep Fat Frying, Lightness, Moisture, Oil Absorption

1. Introduction

Deep-fat frying is one of the oldest procedures for food preparation. It can be defined as a special type of cooking using edible oil at a temperature above the boiling point of water. This temperature generally oscillates between 120°C and 210°C, with 150°C-190°C the most commonly used range[1-2]. The purpose of deep fat frying is to seal the food in hot oil in order to keep flavor and juices within a crunchy cortex and a humid cooked inside[3]. The characteristics of the cortex of fried products are results of the vitreous conditions of low-moisture starch (less than 2%)[4]. Oil immersion is a complex process that involves simultaneous heat and mass transfer, which results in the formation of water vapor (bubbles) and oil countercurrent flows on the surface of food[5-6]. Some other changes that are caused by the frying procedure include: gelatinization of starch, denaturalization of proteins, breaking of cell adhesion (middle lamella) and development of gold coloration, which is one of the decisive attributes for consumer acceptability[7]. In addition, temperatures allow enzymatic deactivation, reduction of intra-cellular air and destruction of pathogenic microorganisms, thus extending food shelf life[8].

Several experimental models of different complexity have been proposed with the purpose of describing

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changes of moisture content during the frying process. Some authors have reported techniques that focus on the process under the theory that mass transfer is controlled by mechanisms of internal diffusion[9]. Diffusivity (D_a, m^2/s) is a property that depends on temperature, pressure and microstructure of the components. High values of this parameter indicate that molecules tend to diffuse easily within a material. On the other hand, the mass transfer coefficient (*kc*) is a constant that indicates the rate (m/s) at which the substance passes through certain surface as a result of concentration differences (driving force)[10]. These two parameters are commonly calculated during frying procedures, since moisture diffuses from the center of the product to the evaporation area, and then to the surroundings through the porous surface. Such phenomenon triggers a slight turbulence in the oil, which in turn leads to the dehydration of the food matrix[2,11]. Moisture transfer has been reported to take place through a highly complex mechanism, since the products are formed by micro and macro-pores through which liquids and gases could diffuse[12-13]. In[14] applied a diffusion model that described the frying process of corn tortillas by assuming infinite-plane geometry, uniform initial moisture and temperature, insignificant shrinkage and constant effective diffusivity[15] developed a 2-dimensional model to predict mass transfer during the frying process of tortilla chips. This model was solved by using the finite element method, achieving a suitable correlation between predicted data and experimental results[1,9] they obtained some mass transfer coefficients when studying potato chips and pieces of yam, respectively. They used an analytical solution of Fick's diffusion equation as a function of time and position on an infinite flat plate with a given thickness. In the same way[8] solved Fick's equation in transient state using spherical coordinates. By doing so, they were able to calculate the effective diffusivity of moisture, along with the mass transfer coefficient for the frying procedure of fish flour-enriched rice cookies. The authors described the dependence of these parameters with process temperature[16], as well as[17] recently applied a mathematical model of diffusion in order to calculate the mass transfer parameters for the deep fat frying of Tulumba Tatlisi (yeastless wheat pudding) and Cheena Jhili (based on refined wheat flour). In these works, high correlations they were achieved between the theoretical and experimental numerical data.

Oil absorption kinetics has been reported to be complex, since the presence of vapor inside the pores of the product will prevent oil flow from happening. Only reduced pressures from vapor condensation will allow oil to be transferred to the product (suction effect), depending on the porosity and permeability properties of the crust[7,18,19]. Many mathematical models have been developed with the purpose of developing healthy food products. These models are focused on the understanding of oil absorption during frying procedures[20] analyzed oil diffusion in fried corn chips and they found that the content of oil on the surface was considerably increased during cooling period. In a similar way[21] and[22] analyzed oil absorption in potato chips and Krostula mass, respectively. These authors applied a first-order kinetic equation and they reported that oil content at equilibrium increased with temperature[18] developed and applied a mathematical model that was based on capillary forces and pressure differences by taking into consideration the cooling period. They pointed out that oil absorption is also governed by microstructural changes in food[23] studied the frying of starch-based snacks and wheat gluten by using a first-order kinetic model. The authors found a linear dependence of oil absorption on process temperature[6,13] recently studied the kinetics of oil absorption during the frying process of Pantoa and cassava snacks, respectively. They reported a significant effect from temperature with activation energies within the scales previously reported by other authors.

Table 1. Formulation used for the preparation of the arepas con huevo

Ingredients	Amount (g)	(%)
Yellow Corn Flour *	120	48
Water*	80	32
Salt*	3.5	1.4
Groundpepper*	1.5	0.6
Eggsofhensize AA	45	18
Total	250	100

*Components of the precooked dough.** Amounts used to make an *arepa con huevo* in a restaurant in the City of Cartagena.

Arepa con huevo (AH) is one of the products with highest consumption in Colombia. It is prepared with flour of corn. This dough is hydrated and mixed with salt. It is then molded into a round disc in which a raw chicken egg is encapsulated without the shell, and the product is then submitted to deep fat frying. This typical food has become a gastronomic tendency that takes part in culture and identity of the Colombian Caribbean Coast[24]. AH is an important product for the economy of many low-income families that depend on its commercialization at public plazas and restaurants. In Luruaco (Atlantico), festivals are held each year with the sole purpose of consuming this product. In addition, there are some specific plans in the area that seek to protect this typical product[24]. So far, there are no studies related to the mass transfer phenomena that take place during the frying process of AH. Thus, this research aims to evaluate the effect of the deep fat frying on mass transfer and color changes of AH.

2. Materials and Methods

2.1 Product Formulation and Preparation

Pre-cooked corn dough from the *cariaco* variety (*ZmCol-CIM-3132*) was used to prepare the AH. This variety had a moisture content of 59.04±4.38 %. A local company from Cartagena (Colombia) supplied it. Upon receipt, the dough was storage under refrigeration at 12°C using a *Frigobar Igloo* 1.7 ft Stainless Steel FR-180 unit. The product was prepared by following the traditional techniques of local vendors. Table 1 shows the formulation that was used during preparation stages of the product. Creole chicken eggs with a growth period of approximately 90 days were used for the preparation process. The eggs were provided by a local trading Company and they had a commercial size AA, average weights of (66.52±2.64) g (with shell) and (45.31±1.82) g without shell. The mass was homogenized for 10 minutes using a professional kneader (Kitchen Aid Model 5K5SS, USA). The product was molded into a 10 cm diameter and 2.5 cm thickness round-geometry, based on the traditional geometry. The results are shown in Table 2. A circular, hollow mold with enough room for both mass and egg was used for this purpose.

2.2 Deep-Fat Frying Process

Commercial palm oil was used as heating medium because of its high resistance to oxidation, low cost and frequent use in similar studies[24-26]. The oil was purchased at a local market of Cartagena (Bolivar). Electric, stainless steel, 7 L fryer was used. This unit had three thermocouples (Type J, 304 stainless steel) with a diameter of 0.25 mm to allow control of oil temperature at the center and surface of the product (precision around ±0.05°C). These elements were coupled to a laptop with a data gathering system (INTECH Micro 2100-A16 Rev 1.3) and a PID controller (RKC HA 900 Instrument USA). Prior to the frying stage, the round plates of corn dough were put in the hollow mold for 1 minute at room temperature (25°C) and one chicken egg without shell was added to each one of them. Another plate was then used to seal the product, leaving the egg in the inside of the corn dough. The deep fat frying was carried out once oil had reached temperatures of 170, 180 and 190°C, after approximately 30 minutes. At this point, the AH were submerged using a small metal grid basket that allowed the total immersion of the product. Frying times were around 30 and 420 s. Oil-product ratio was 1:4 weight/volume (250 g/L), and the oil was renewed every 3 hours of continuous process. The AH were subsequently removed from the fryer and placed in a small metal grid basket where they were left to drain by gravity for 2 minutes at room temperature. Lastly, the product was deposited in desiccators until final analysis.

2.3. Kinetics of Moisture Loss

A completely randomized experimental design with a 6x3 factorial structure was used in this stage. The first factor had six levels that corresponded to frying time (30, 60, 120, 180, 300 and 420) s and the second factor was temperature, with three levels (170, 180 and 190) °C. Thus, 18 basic combinations were obtained, and moisture measurements in the LT04/5 convector furnace (Method 925.09 - A.O.A.C)[27], were carried out by triplicate for each treatment until achieving constant weight at 105°C. A total of 54 experimental units (EU) were obtained. The data was expressed as averages with their respective mean standard deviation on a dry basis (g water/g dry solid).

2.4 Calculation of Diffusion (D_a) and Convection (kc) Coefficients

In order to determine the effective diffusion (D_a) and convective mass transfer (k_c) coefficients of AH, moisture diffusion was considered to be mono-dimensional, as described by Fick's second law. This law is based on the following assumptions: the solid is homogeneous and isotropic, the initial temperature is uniform and the shape of the product remains unaltered over time. Therefore, this study works with an entire round plate with constant initial moisture (C_i) and thickness of 2L from the origin (x=0) and defined in the range $-L<x<+L$, which is submerged in oil at a controlled temperature. The diffusion mechanism is described by Equation (1):

$$\frac{\partial C}{\partial t} = D_a \frac{\partial^2 C}{\partial x^2} \qquad 0 \le x \le L; \text{ for } t > 0 \tag{1}$$

Initial condition is set at t=0, contour at x=0 and contact surface with the surroundings at x=+L, as it is shown in Equations (2), (3) and (4), respectively:

$$C(x, t=0) = C_i \tag{2}$$

$$D_a \frac{\partial C}{\partial x} = 0, \text{ in } x=0, \text{ and } t>0 \tag{3}$$

$$-D_a \frac{\partial C}{\partial x} = k_c (C - C_\infty), \text{ in } x = L \text{ and } t > 0 \tag{4}$$

Where: D_a is the effective diffusivity of moisture. L is the semi-thickness of the plate, k_c is the mass transfer coefficient, C(x = 0, t) is the water concentration (dry basis) at a given time. C(x = L, t) is the water concentration on the surface of the plate (dry basis) and C_∞ is the equilibrium moisture with the surroundings (dry basis), which was assumed as neglectable in this specific case, since water content of oil was closed to zero. Therefore, the analytical solution of differential equation (1) can be expressed in terms of the infinite series that is schematized in Equation (5)[10] and[26], have applied the solution of this equation, in their studies of potato chips, shrimp chips and cassava slices, respectively:

$$\left(\frac{C(x,t) - C_\infty}{C_i - C_\infty}\right) = \sum_{n=0}^{n=\infty} \frac{2\text{Sen}\delta_n}{\delta_n + \text{Sen}\delta_n + \text{Cos}\delta_n} \text{Cos}\left(\delta_n \frac{x}{L}\right) e^{-\delta_n^2 \frac{D_a t}{L^2}} \tag{5}$$

Equation (6) is obtained by taking the first term of Equation (5) (n=1) for ($Fo = \frac{D_a t}{L^2} > 0.2$) and integrating with respect to the entire volume $,\bar{C}(t) = (\frac{1}{V}\int_0^V C(x, t)\, dV)$. The o btained result was used to calculate the global concentration of moisture in a round, infinite plate as a function of time:

$$\left(\frac{\bar{C}(t) - C_\infty}{C_i - C_\infty}\right) = \frac{2\text{Sen}\delta_1}{\delta_1 [\delta_1 + \text{Sen}\delta_1 + \text{Cos}\delta_1]} e^{-\delta_1^2 \frac{D_a t}{L^2}} \tag{6}$$

Where: $\bar{C}(t)$ is the average concentration of moisture (dry basis) at a given time; When applying logarithms, Equation (7) is obtained:

$$Ln \frac{\bar{C}(t) - C_\infty}{C_i - C_\infty} = Ln \frac{2\text{Sen}^2\delta_1}{\delta_1 [\delta_1 + \text{Sen}\delta_1 + \text{Cos}\delta_1]} - \delta_1^2 \frac{D_a t}{L^2} \tag{7}$$

This Equation was adjusted to the line $y = A - bt$, with time (s) being set to the X axis, and the dimensionless moisture concentration to the Y axis. Upon plotting, the positive square root was calculated from the origin ordinate, as indicated in Equation (8):

$$A = Ln \frac{2\text{Sen}^2\delta_1}{\delta_1 [\delta_1 + \text{Sen}\delta_1 + \text{Cos}\delta_1]} \tag{8}$$

The search range for δ_1 was set from ($0 < \delta_1 < \pi/2$). Once this value was found, it was used along with semi-thickess (L_2) and slope (b) to calculate the diffusion coefficient D_a for each temperature through equation (9):

$$Da = \frac{L^2 b}{\delta_1^2} \tag{9}$$

The convective mass transfer coeffcient was then calculated based on the deffinition of the mass transfer Biot number for a round plate, as described by Equation (10):

$$Bi_m = \delta_1 \tan \delta_1 = \frac{k_c L}{D_a} \tag{10}$$

The dependence of effective diffusion of moisture with temperature was adjusted by using Arrhenius-like Equation (11), in order to calculate activation energy of the process.

$$D_a = D_0 \exp\left(\frac{-E_a}{RT}\right) \tag{11}$$

This equation was linearized and expressed as Equation (12):

$$\text{Ln } D_a = \text{Ln } D_0 - \frac{E_a}{R} \cdot \frac{1}{T} \tag{12}$$

Where D_0 is the pre-exponential factor associated to absolute reaction rate, E_a is the activation energy (kJ mol^{-1}), R is the universal gas constant (8.31 kJ mol/K) and T is absolute temperature (K). E_a was obtained from the slope after plotting $\text{Ln } D_a$ vs $\frac{1}{T}$. It represents the energy that is required to start dehydration of the product.

2.5 Kinetics of Oil Content

A completely randomized experimental design with a 6x3 factorial structure was used in this stage. The first factor had three levels that corresponded to temperature (170, 180 and 190°C) and the second factor was frying time, with six levels (30, 60, 120, 180, 300 and 420)s. Oil content was determined by extraction with petroleum ether (Method 920.85 – A.O.A.C)[27]. Thus, 18 treatments with triplicate measurements were obtained, for 54 EU. The results were expressed as dry basis average (g oil/g dry solid without oil) with their respective standard deviations.

2.6 Calculation of Oil Absorption Rate

The rate of oil absorption during the frying process of AH was described by using the empirical model proposed by[21]. This model is represented in Equation (13) and[28] applied it, when frying Gethi strips.

$$O^* = O_{eq}\left(1-e^{-Kt}\right) \tag{13}$$

O* represents the oil content at time t (dry basis), O_{eq} is the oil content at equilibrium (dry basis) when $t = \infty$. At $t = 0$, oil content is minimum and it reached a maximum value after long periods of time. The experimental data of oil content over time was used to adjust the equation to a straight line. The value of K was calculated from the slope when plotting $\mathrm{Ln}\left(1-\frac{O^*}{O_{eq}}\right) vst$. This constant represents the specific rate of oil absorption (s^{-1}). The relation between oil content at equilibrium O_{eq} and frying temperature was described by using an Arrhenius-type relation from which activation energy of the process could be obtained. Equation (14) shows this relation:

$$O_{eq} = O_0 \exp\left(\frac{-E_a}{RT}\right) \tag{14}$$

Where: O_0 represents a constant pre-exponential factor, E_a is the activation energy, R is the universal gas constant (8.31 kJ mol/K) and T is absolute temperature. The activation energy is obtained from the slope by linearizing this expression and plotting LnO_{eq} vs $\frac{1}{T}$. The parameters of these equations were estimated by linear regressions using the *Solver* tool of *Microsoft Excel*, *2013* (Microsoft Corp.). Root mean square (RMS) was set as target function, as it can be seen in Equation (15):

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{V_1-V_2}{V_1}\right)^2} \tag{15}$$

There, N represents the number of data points, V_1 experimental value and V_2 adjusted value. Model adjustment was expressed in terms of correlation coefficients (R^2) and significance level ($p<0.05$).

2.7 Color Analysis

A completely randomized experimental design with a 5x3 factorial structure was used in this stage. The first factor had three levels that corresponded to temperature (170, 180 and 190) °C, and the second factor was frying time, with five levels (30, 60, 120, 180 and 300) s. Thus, 15 combinations with triplicate measurements were obtained, for 45 EU. Whole samples of AH were used for this stage, using CR-5 reflectance colorimeter (*Tristimolo Konica Minolta Sensing*) with D_{65} light source and atone angle of 10°. This unit was calibrated with a white plate accessory. The parameters were evaluated by following a *CIEL *a*b* system methodology in regards of luminosity *L** (light – dark), chromaticity *a**, red (+) and green (-), and chromaticity *b**, yellow (+) and blue (-). General color change (*ΔE*) with regard to the unprocessed (standard) product was calculated in a similar way by using Euclidian distance, as shown in Equation (16):

$$\Delta E = \sqrt{\left(L^*-L\right)^2+\left(a^*-a\right)^2+\left(b^*-b\right)^2} \tag{16}$$

Where *L*a*b** are the values of each treatment and *L, a, b* correspond to the product before frying. All the essays were performed by triplicate, and data was expressed as averages with their respective standard deviation.

2.8 Statistical Analysis

Each average of the response variables was processed using the statistical software *Statgraphics Centurion* 16.1.15 (Corporation, U.S.A.). An ANOVA and Tukey's HSD multiple comparison test were applied in this stage with a level of significance of 5% ($p\leq 0.05$).

3. Results and Discussions

3.1 Kinetics of Moisture Loss

Figure 1 shows the kinetic behavior of moisture loss during the deep-fat frying of AH. Similar dehydration rates were observed during the first stage (30 to 90 s) at the three studied temperatures ($p>0.05$). After 120 s of frying time, some statistical differences between the moisture content of the AH that were fired at lower temperatures and those that were processed at 190°C became evident ($p<0.05$). In addition, once 300 s had passed, moisture content reached a maximum value of 34.11 % ±1.15% in the AH that were processed at the highest temperature. Values of 8.44 % and 21.11% moisture content were obtained when working with temperatures of 180°C and 170°C, respectively. High temperatures had a negative, statistically significant effect on moisture content of the samples that were processed under all conditions. At the end of the process (420 s, bubble point without superficial burnings), the equilibrium moisture at the three different temperatures in decreasing order represented total losses of 57.65 %, 51.73 % and 40.72 % with regard to the unprocessed product. This demonstrates that deep fat frying acted as a drying process within the microstructure of AH. It has been reported that the free moisture content of starchy food products undergoes a fast vaporization stage during frying processes by the action of increasing internal energy. This vapor exerts a partial pressure within the pores of the crust, which promotes the development of porosity and accelerates dehydration[14,22,29,30]. Changes on moisture content of AH might be explained by such phenomenon.

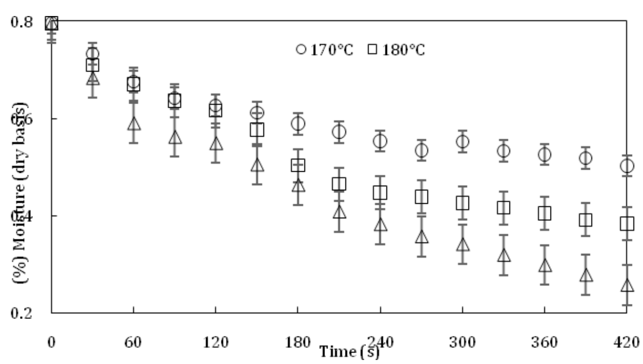


Figure 1. Kinetic curves of the loss of moisture of the arepas con huevo at the different times and temperature of frying. The values represent the averages with their standard deviation (g water/g drysolids).

These results are in agreement with the ones that were reported by[5] in his study on wheat-flour-covered-shrimp nuggets. They found that moisture content was significantly reduced with increasing times and temperatures. The authors attributed this behavior to the increase of internal energy, as well as the development of superficial porosity within the product. Numerous researchers have found that the excess crust formation during the early stages of the process could act as a barrier for heat transfer, hindering both vaporization of internal moisture and liquid diffusion through the microstructure. These conditions might in turn affect the internal gelatinization of starch, which would result in products with burnt crispy exteriors and raw inner content. Thus, it becomes highly important to control and understand changes in moisture content during the frying process, since these changes can help optimize the process and the quality of food matrices[8]. It should be noted that water was added to corn dough during preparation with the purpose of softening the structure and allowing its molding into circular plates[31] studied soy protein-enriched Arepas from white corn, and they claim that high-quality dough should present initial moisture contents between 50 % and 65% (w/w), since it is responsible for texture, shape and dehydration rate of the products once they are submitted to high temperatures. The moisture content of AH was attributed to corn dough, to the addition of water during kneading, and to the water content of raw egg. Similar products have been reported to experience hydration in their starch granules during consecutive kneading over long periods of time[8,16,32]. These granules are then partially gelatinized as a result of constant movement and energy input in the form of friction heat. Such phenomenon might result slightly favorable, since different studies have shown that pre-gelatinized starch could prevent excessive dehydration of starchy products during frying processes[33].

3.2 Calculation of Mass Transfer Parameters

3.2.1 Effective Moisture Diffusivity

The rate of moisture loss during the first 15 s was characterized by the sudden vaporization of superficial moisture. Such behavior might not be linear, since the turbulence of vapor bubbles created instability at the food-oil interphase[30]. Therefore, this phase was not taken into consideration when calculating the diffusivity coefficient for the deep fat frying of AH. However, this initial stage was followed by a period of constant vaporization rate until formation of the crust, since the vaporization front was relocated to the insides of the product[18]. Figure 2 details the dimensionless relation between moisture content *vs* frying time of AH. Such relation was obtained by linear regression. As it can be seen, the rate of moisture loss increased with temperature and time ($p<0.05$), with a higher slope and adjusted correlation coefficient (R^2 = 0.99) at a temperature of 190°C.

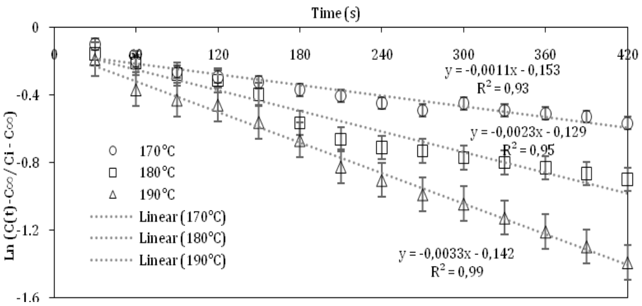


Figure 2. Logarithm of the non-dimensional moisture concentrations of arepas con huevo with respect to the frying time at different temperatures.

Table 2 shows the values of moisture diffusivity and the mass transfer coefficients that were calculated for deep fat fried AH. It should be noted that diffusivity experienced a significant increase with increasing time and temperature ($p<0.05$), varying from ($1.75\pm0.01 \times 10^{-7}$) m^2/s at 170°C ($R^2 = 0.93$) up to ($5.03\pm0.06 \times 10^{-7}$)$m^2/s$ at 190°C ($R^2 = 0.99$). Moisture diffusivity of starchy materials undergoing frying conditions has been reported to increase with porosity and initial moisture content[23]. In a similar way, low-porosity food products have low diffusivity coefficients, since the release of water vapor from the microstructure is highly restricted[7]. The results that were obtained for AH are highly similar to those reported by[14]. They obtained values between (0.54×10^{-7} and 0.93×10^{-7}) m^2/s when studying fried corn chips at temperatures between 150 °C and 190°C. The findings were also close to the ones that were obtained by[5]. On their research, they found that the effective moisture diffusivity ranged from (2.05×10^{-8} and 5.71×10^{-8})m^2/s, with R^2 between 0.91 and 0.98.

In[1] also indicated diffusivity values of 1.95×10^{-9}, 2.59×10^{-9} and $3.24\times10^{-9} m^2/s$ when studying fried yam at temperatures of 140, 160 and 180°C[22] reported diffusivity values of (5.83×10^{-9}, 6.60×10^{-9}, 8.47×10^{-9} and 9.72×10^{-9}) m^2/s in their work regarding fried *Krostula* at temperatures of 160, 170, 180 and 190°C, respectively. These results are also close to the ones reported by[9] when studying the frying process of potato slices[34]. The authors reported that moisture diffusivity increased linearly with temperature, obtaining values of (1.12×10^{-7}; 1.58×10^{-7} and 2.04×10^{-7}) m^2/s at (150, 170 and 190) °C, respectively[10] used the same temperature range when studying fried sweet potato and they reported diffusivities of (9.19×10^{-7}, 10.70×10^{-7} and 13.90×10^{-7})m^2/s for the control samples, and (9.52×10^{-7}, 12.31×10^{-7} and 15.32×10^{-7})m^2/s for carboxymethyl cellulose-covered chips. Different studies have also found effective diffusivity coefficients of (1.24×10^{-8}, 1.60×10^{-8} and 2.36×10^{-8})m^2/s for fish flour-covered rice cookies and (1.27×10^{-8}, 1.61×10^{-8}) and (2.36×10^{-8})m^2/s for control samples at 170, 180 and 190°C, respectively[8,30] obtained moisture diffusivities between (5.41×10^{-9})m^2/s and (6.91×10^{-9})m^2/s at temperatures between 170°C and 190°C after 900 s of frying time.

In a similar study[34] indicated that the diffusion coefficient of pre-treated potato chips ranged between (13.02×10^{-9} and 9.83×10^{-9})m^2/s at temperatures between 120°C and 180°C[35] used a different variety of potatoes and they obtained effective diffusivity values between (4.73×10^{-9} and 1.80×10^{-8})m^2/s at temperatures from 120°C to 140°C, which actually represent the lowest temperatures that were used for AH[36] reported values of diffusivity between (1.47×10^{-8} and 4.17×10^{-8})m^2/s, while[6] found effective diffusivity coefficients from (5.55×10^{-8} to 38.81×10^{-8})m^2/s. On the other hand[16] calculated moisture diffusivity coefficients of (1.77×10^{-7}, 2.15×10^{-7}, 2.69×10^{-7} and 3.59×10^{-7})m^2/s when studying the deep fat frying of *tulumba* dessert at temperatures of (150, 160, 170 and 180) °C. In general, these values of moisture diffusivity for AH were much higher than the ones calculated by[37]. They reported values between (20.93×10^{-10} and 29.32×10^{-10})m^2/s, attributing the differences to the microstructure and chemical composition of the product, as well as processing conditions and calculation methods employed.

3.3 Mass Transfer Coefficient

The mass transfer coefficients that were calculated for AH revealed a statistically significant increase ($p<0.05$) with process temperature and time. The values started at ($4.26\pm0.31\times10^{-6}$)m/s ($R^2 = 0.94$) at 170°C and reached ($9.58\pm0.81 \times 10^{-6}$)m/s ($R^2 = 0.99$) at 190°C. These results were similar to the ones reported by Ortega and Montes (2014) when studying cassava chips. They obtained coefficients around (1.37×10^{-5} and 7.37×10^{-5})m/s with linear behavior about oil temperature, while found values between (0.78×10^{-6} and 3.31×10^{-6})m/s at 140 °C and 180 ºC, respectively. On the other hand[10] calculated values of (3.81×10^{-4}, 7.66×10^{-4} and 10.24×10^{-4})m/s when studying non-covered samples and (3.57×10^{-4}, 4.78×10^{-4} and 7.67×10^{-4})m/s for covered-products[11] calculated the *kc* coefficients for the deep fat frying of sweet potato slices at temperatures of 150, 160, 170 and 180°C. Reporting maximum values of ($4.9x10^{-6}$, $5.7x10^{-6}$, $7.0x10^{-6}$ and $7.3x10^{-6}$) m/s.

In[8] reported coefficients of ($5.51x10^{-6}$, $7.06x10^{-6}$ and $9.31x10^{-6}$)m/s when studying samples with fish flour, with values ($5.98x10^{-6}$, $7.46x10^{-6}$ and $9.70x10^{-6}$) m/s for the control samples that were fired at (150, 170 and 190)°C respectively. On the other hand[29] found that the mass transfer coefficient of fried *Gulabjamun* was linearly increased with temperature, varying from ($10.41x10^{-6}$ and $14.35x10^{-6}$)m/s at temperatures between 135°C and 155°C[6] obtained coefficients of $7.79x10^{-6}$ and $9.05×10^{-6}$ m/s between 125 and 145°C[16] recently found *kc* coefficients of ($3.09 x 10^{-6}$, $3.24 x 10^{-6}$, $3.45 x 10^{-6}$ and $3.69x10^{-6}$) m/s at temperatures of (150, 160, 170 and 180)°C, respectively. In the same way[17] found that these coefficients were increased from ($2.85x10^{-6}$ to $7.54x10^{-6}$)m/s at temperatures of 120°C and 140°C. These values are close to the ones that were found for AH.

3.4 Dependence of k_c with Temperature and Activation Energy

Figure 3 outlines the behavior of the mass transfer coefficient with process temperature. As it can be seen, there is a linear and highly significant relation between the variables ($p<0.05$). Figure 4 shows the Arrhenius-type adjustment between the logarithm of the diffusivity coefficient and inverse temperature. This data was used to calculate the activation energy of moisture loss during the frying process of AH. The pre-exponential factor (D_0) of moisture loss was found to be 1.04 $x10^{-2}$ (s^{-1}), for an E_{ra} of 63.96 kJ/mol. Equations (17) and (18) describe the behavior of diffusivity and mass transfer coefficients as a function of temperature.

$$D_a = 1.04x10^{-2} \exp\left(\frac{7.68x10^3}{T}\right) R^2 = 0.97) \quad (17)$$

$$k_c = 2.44x10^{-7}T - 3.25x10^{-5}(R^2 = 0.99) \quad (18)$$

The obtained E_a of moisture diffusion was higher than the one reported by[22], who reported a value of 30 kJ/mol. The result is also higher than the ones obtained by[35,5]. These authors found values between 23.51-29.36 kJ/mol and 18.42-23.86 kJ/mol, respectively. High E_a have been reported to indicate difficulties in removing moisture from food products[36] indicated that this parameter ranged between 38.34 and 51.07 kJ/mol. In a similar way[23,28] found E_a of 28.68 kJ/mol and 41.53 kJ/mol (R^2> 0.99 and $p <0.01$), while[16] reported a value of 36.58 kJ/mol. These represent lower activation energies than the ones obtained for AH. In general, diffusive activation energy represents the energy that is required to dehydrate the food matrix during thermal processing. Activation energy values below 95 kJ/mol are commonly linked to starchy products with low water activities. This is explained by the strong substrate-water interactions, which lead to higher energy input when removing moisture and starting diffusion within these types of materials[13].

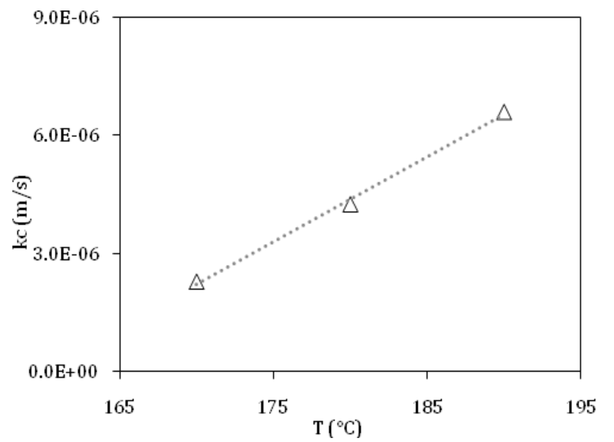


Figure 3. Dependence of the mass transfer coefficient with respect to the frying temperature.

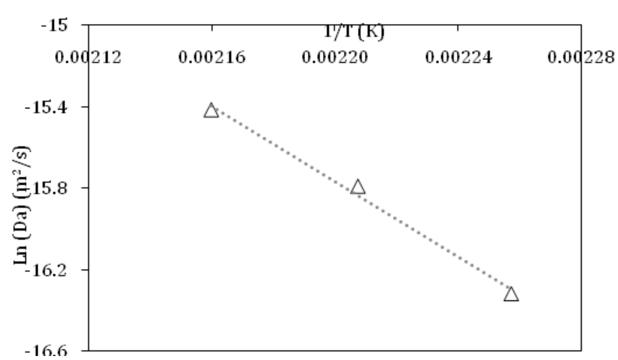


Figure 4. Effective moisture diffusivity during frying and its dependence with temperature.

The activation energy that was obtained for AH is slightly higher than that of referenced researches. Such result is attributed to differences in microstructure and superficial porosity of the product. These two factors would make moisture difficult at the end of the process. Thickness of the samples, which was larger than the one commonly used in potato chips, corn snacks and different starchy products, might have also influenced the results[17,26]. It is desirable for fried products to present low moisture contents, since it provides suitable stability by inhibiting the metabolic action of microorganisms that cause decomposition. Thus, the prediction of moisture loss through mass transfer parameters becomes highly important. Calculation of activation energy is also indispensable, to not only develop and apply models of thermal procedures, also to optimize treatment conditions and quality of the food matrices.

3.5 Kinetics of Oil Absorption

Figure 5, shows the behavior of the oil absorption kinetics for AH at the different frying times and temperatures. It should be noted that the initial absorption rates were quite high and lead to no significant differences between the samples that were fried the three different temperatures ($p>0.05$). However, starting at 180 s, the oil content of AH at low temperatures was higher than that of the AH that were processed at high temperatures ($p<0.05$). An equilibrium value is reached after 300 s, with final increases of 40.65%, 26.29% and 18.28% after 420 s when compared to the unprocessed product at (170, 180 and 190)°C, respectively. This indicates that high frying temperatures lead to lower oil content of AH, despite the fact that the product presented less moisture at such conditions. This reflects that the oil absorption rate of this product was not related to moisture loss, but it is rather attributed to changes in microstructure. The higher formation of superficial crust also influences absorption by acting as a physical barrier that prevents oil from entering the structure[22,25].

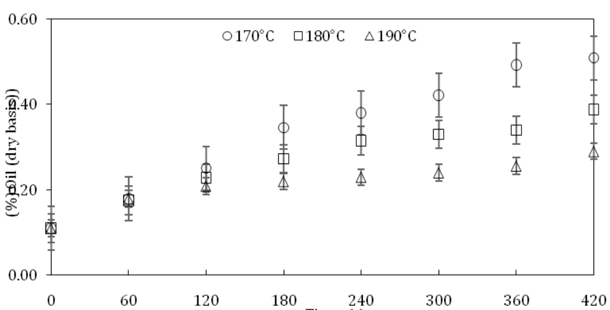


Figure 5. Kinetics of oil absorption during frying of arepas con huevo. Values represent the averages of three replicates with their standard deviation (g dry oil/g dry oil-free).

In addition, the processing conditions that were applied could have caused microstructural damages to the product about the gelatinization of starch granules, which influences oil absorption[14,29]. Indicated that the pore size developed in corn tortillas was the main factor that influenced oil content. Some other authors have pointed out that the decrease in the rate of oil absorption is caused by the fact that most part of the intercellular spaces on the surface becomes cluttered with oil as time passes by[2]. The results that were obtained for AH are in agreement with the ones reported by[19] in regards of their study with potato chips. They found that oil absorption was increased by 32% when reducing frying temperature from 180°C to 120°C. On the other hand[4] reported that high frying temperatures promoted oil absorption. They found a positive and highly significant correlation between both variables ($R^2>0.95$ y $p<0.05$) at times of (45 to 600)s. Such phenomenon was attributed to porosity development over temperature.

3.6 Oil Absorption Rate and Activation Energy

Figure 6 outlines the behavior of the oil absorption rate in AH. The data was adjusted by linear regression for the first 300s, when the product experienced changes from 11% in average up to (42.03±0.63) % at 170°C, (33.98±0.22) % at 180°C and (24.93±0.48) % a 190°C. The specific rate of oil absorption in the product *K* was calculated from the slope of the linear sections that are obtained by plotting these values. Table 3 shows the parameters of oil absorption and activation energy that were calculated for AH.

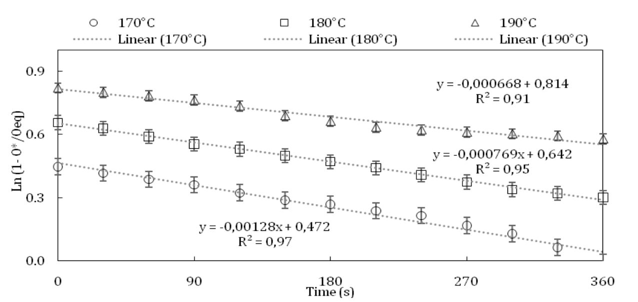


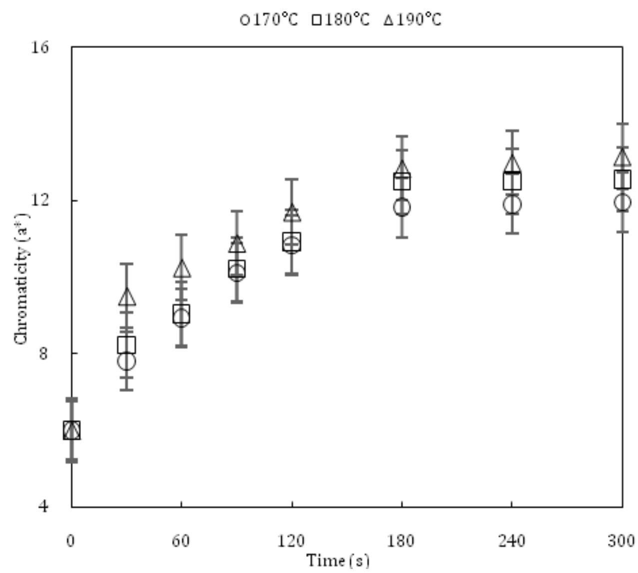
Figure 6. Linear regression of the kinetic model describing the oil absorption of arepas con huevo during frying. The data represent the average with its standard deviation.

The values of root mean square (RSM) and R^2 indicate a suitable adjustment between the kinetic model and experimental data. Troncoso and Pedreschi[35] reported similar results. Temperature had a reverse, significant effect ($p<0.05$) on the absorption rate, with *K* values between $1.28±0.06x10^{-3}$ at 170°C ($R^2 = 0.97$) and (0.67

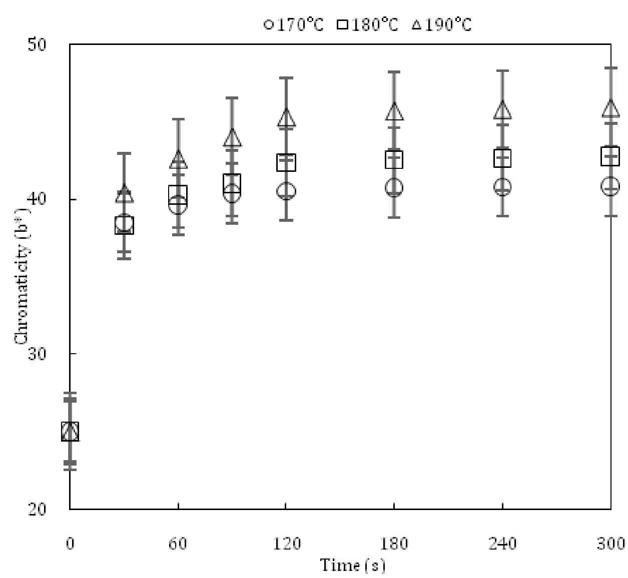
± 0.04x10^{-3})s^{-1}(R^2 = 0.97) at 190°C. These results were similar to the ones found by[5] who reported values of K between (7.80x10^{-3} and 3.50 x 10^{-3})s^{-1}, with R^2 of 0.99 and 0.82, respectively. On the other hand[28] obtained results ranging from (2.31x10^{-3} to 7.16´10^{-3})s^{-1} (0.139 at 0.43 min^{-1}), which clearly shows an increase with temperature between 120°C and 180°C. In regards to this[36] reported coefficients from (2.40´10^{-2} to 0.19´10^{2})s^{-1} at temperatures between 135°C and 160°C. In a similar study involving fried chickpea snacks[32] reported coefficients between (5.60´10^{-2} and 8.20´10^{-2})s^{-1} using temperatures from 150°C to 200°C. The results that were obtained in these two last studies were higher than those found when studying AH were. Such difference can be attributed to variability in composition, thickness and microstructure of the processed products. AH presented an E_a value of 50.66 kJ/mol (R^2 = 0.99 and p <0.01), which is slightly lower than the one reported by[23], 60.39 kJ/mol, and slightly higher than the one calculated by[28], 27.12 kJ/mol. It has been reported that E_a represents the energy that is required to start oil absorption in fried products. Starchy products such as AH are frequently linked to E_a between 15 and 95 kJ/mol[17,22,25].

3.7 Color Changes of AH

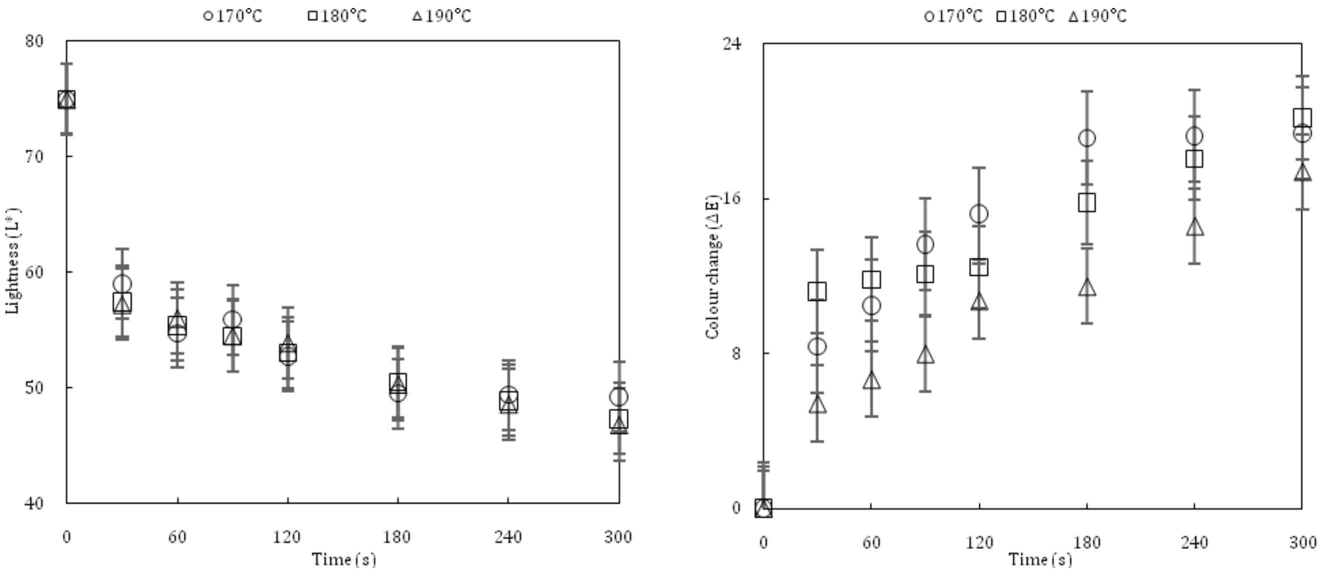
Figure 7 describes the variations in color in regards of values (a* and b*), lightness (L*) and general color change (ΔE) in deep fat fried AH. The chromatic parameters experienced a significant variation with increasing factors ($p<0.05$). In the case of a*, there was a significant increase ($p<0.05$) when compared to the non-fried product, with values starting at 6.01±0.07 at 25°C, and increasing up to 11.95±0.54, 12.55±0.63 and 13.15±0.77 at(170, 180 and 190)°C respectively. On the other hand, b* values evidenced significant differences ($p<0.05$) regarding color of the non-fried products. This parameter went from 25.06±0.09 at 25°C, to 40.85±0.07 at 170°C, 42.79±0.09 at 180°C and 45.97±0.14 at 190°C. Such behavior indicates that the AH acquired a red and yellowish tone on their surface, possibly because of the color changes of pigments within the microstructure of corn dough. It is believed that high temperatures are responsible for the alteration and development of such coloration. In the same way, the increase of a* and b* values can be attributed to the fact that part of the frying oil was adhered to the crust. Initially, the oil presented a natural pale yellow coloration before experiencing deterioration, but it then acquired a light red tone after the thermal process[24,25]. On the other hand, the L* values of AH experienced a significant decrease ($p<0.05$), especially after the first 30s of frying time. Lightness varied from 75.02±3.42 (before deep-fat frying) to 49.25±2.34 at 170°C, 47.32±2.16 at 180°C and 46.82±2.28 at 190°C. These results demonstrate that the product is browned after the frying process, and that changes in L* are produced in the same proportion of temperature variation. By analyzing ΔE, it was observed that significant differences were achieved on all treatments ($p<0.05$). When comparing these values with those of the products that were fried at 300s, it was found that the samples that were processed at 180°C presented



(a)



(b)



(c) (d)

Figure 7. Variation of the color parameters of the fried arepas con huevo at the temperatures of 170, 180 and 190) °C. (b) Chromaticity a *, (b) Chromaticity b *, (c) Lightness L * (d) Colour change. The data represent the average with its respective standard deviation.

the highest variation, with values of 20.17±3.68. This result is slightly higher than the one obtained at 190°C (17.41±3.05). Nonetheless, no significant differences between these ratios were detected by ANOVA with a time of 300s (p>0.05).

The changes in L^* and ΔE in of AH could be attributed to caramelization reactions and to the non-enzymatic browning between reducing sugars and free amino acids within the corn dough[24,25]. Starchy products have been reported to develop coloration upon experiencing dehydration because of the deep-fat frying[17]. This would explain the behavior of AH with frying time and temperature increase. Such results were similar to the ones reported by[33] when studying the deep fat frying of some

Table 2. Mass transfer parameters of the fried arepas con huevo (moisture diffusivity, biot number and convective coefficient)

Temperature (°C)	***Slope (b) x10^{-3}**	**Intercept (A)**	**R^2(adjusted)**	***D_a x 10^{-7} m^2/s**	**Biot**	***k_c x 10^{-6} m/s**	**E_a (kJ/mol)**
170	1.14 ± 0.02	0.15	0.93	1.75 ± 0.01	5.25	4.26 ± 0.31	63.96
180	2.23 ± 0.08	0.13	0.95	3.56 ± 0.08	4.38	6.31 ± 0.45	
190	3.33 ± 0.07	0.14	0.99	5.03 ± 0.06	4.78	9.58 ± 0.81	
Average	2.26 ± 0.06	0.14	0.94	3.45 ± 0.03	4.81	6.72 ± 0.52	

* Values represent the averages of three replica test standard deviation.

Table 3. Parameters describing the oil absorption kinetics of the arepas con huevo and the activation energy with Arrhenius type adjustment

Oilabsorptionrate					Activationenergy			
T (°C)	*K x 10^{-3} (s^{-1})	R^2	% RSM	1/T (Kelvin) x10^{-3}	LnOeq (drybasis)	*Slope	R^2	Ea (kJ/mol)
170	1.28 ± 0.06	0.97	1.35	2.25	-0.69	6131.4 ± 45.97	0.99	50.66
180	0.77 ± 0.02	0.95	1.42	2.21	-0.98			
190	0.67 ± 0.04	0.91	1.16	2.16	-1.36			

* Values represent the averages of three replica tes standard deviation.

formulated food products containing starch, gluten and non-soluble fiber. The authors indicated that the decrease of L^* and ΔE was attributed to a lower water activity (<0.9), which had possibly promoted Maillard reactions. In their study regarding fried *Gulabjamun*[38] indicated that the L^* values were decreased as the process continued, varying from 79.86 in fresh samples to values of (23.48 at 120) °C and (29.25 at 140) °C. While that[39] studied the effect of deep fat frying on the color changes of *Bezhy* (wheat cookie) using first-order kinetics, reporting a significant decrease in L^*. This parameter varied from (86.30, 78.81 and 75.28 to 72.85, 38.98 and 37.98 at 150, 165 y 180) °C, respectively. Such phenomenon was attributed to the non-enzymatic browning and superficial caramelization reactions within the product[40] studied the frying process of tofu (soy-based product) at temperatures between 147°C and 172°C, and they reported a reduction in L^*, from 85.51 to 68.01. The authors also found that redness (a*) and total change (ΔE) experienced a rapid increase after 15 s, and even faster changes at high temperatures, which caused variations from -1.17 to 6.72 and from 0 to 26.71, respectively. On the other hand, yellowness (b*) was increased from 18.1 to 34.51, and later reduced to 29.41. These authors indicated that all color parameters complied with first-order kinetics, since suitable correlations were observed between the experimental and predicted data.

4. Conclusions

Temperature and frying time had a significant effect on the moisture loss of AH. Diffusivity (D_a) and mass transfer (k_c) coefficients increased along with the level of factors. The dependence of moisture diffusivity was described with an Arrhenius-type equation, and its activation energy was calculated at 63.96 kJ/mol. Oil content of AH was not linked to moisture loss. This was attributed to the changes on the superficial structure, such as cluster formation and the possible development of porosity with temperature. The oil absorption rate was reduced with increasing temperatures, and activation energy of 50.66 kJ/mol was found. It is possible to produce AH with low oil content by frying them at 190 °C. Lightness was decreased with increasing temperatures, while the chromatic values, as well as general color change experienced a significant increase when increasing both factors. The understandings of mass transfer parameters, as well as color changes during the deep fat frying of AH, are important elements for the design and optimization of similar thermal process that could be applied to this product.

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