Journal of Food Science and Technology (Iran)

Homepage: www.fsct.modares.ir

Scientific Research

Analysis of heat and mass transfer during hot air frying and deep frying of shrimp

Bahareh Maroufpour[1], Aman Mohammad Ziaiifar[*2], Mohammad Ghorbani[3], Hassan Sabbaghi[4], Saeed Yalghi[5]

1 Ph.D. student of food industry science and engineering, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

2* Professor, Department of Food Industry Engineering, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran (corresponding author)

3 Professor, Department of Food Chemistry, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran

4Assistant Professor, Department of Food Science and Technology, Faculty of Agriculture and Animal Science, University of Torbat-e Jam, Razavi Khorasan Province, Iran

5 Assistant Professor of Fisheries Department, Golestan Province Fisheries Research Center, Gorgan, Iran

ARTICLE INFO

Article History:

Received:2023/11/29

Accepted:2024/5/12

Keywords:

Shrimp,

Hot air frying,

Mass transfer,

Heat transfer.

DOI: 10.22034/FSCT.22.161.86.

*Corresponding Author E-

ziaiifar@gau.ac.ir

ABSTRACT

In this research, transfer phenomena during hot air frying and deep frying were investigated. Hot air frying (HAF) and deep frying (DFF) were carried out at 160 °C for 15 minutes for shrimp cylindrical pieces. Temperature variations at the product's core were recorded using a T-type thermocouple equipped Data Logger and PicoLog software on a computer. Moisture content and oil of the product were determined. Heat and mass transfer parameters estimate by using the logarithmic plot of dimensionless temperature against time and empirical equations. Results showed that Mass and heat transfer parameters during hot air frying were lower than deep frying method. In deep frying, the Biot number and the effective diffusion coefficient were higher than the hot air frying method. The kinetic constant of moisture reduction in the product was higher in the deep frying method.

1- Introduction

Shrimp, along with salmon, is among the most important commercial fish products in the world. Seafood, such as shrimp, is a staple in many countries' diets, and currently, the demand for these products as an excellent source of polyunsaturated fatty acids, particularly omega-3 and other fatty acids, is increasing. The per capita annual consumption of shrimp in the United States has been steadily rising. The shrimp industry is highly significant in South Atlantic and Gulf Coast regions, making shrimp one of the most important species for seafood production [1]. Shrimp belong to the crustacean family and are considered one of the most economically important types of seafood worldwide. Nutritionally, shrimp protein has high bioavailability, as it is easily digestible compared to proteins from other sources [2]. Shrimp is a rich source of vitamin B-12, selenium, omega-3 polyunsaturated fatty acids, and astaxanthin, which has been shown to provide antioxidant support for the nervous system and musculoskeletal system. Additionally, some studies have shown that it may reduce the risk of colon cancer by absorbing astaxanthin and decreasing the risk of certain diabetes-related issues [3].

Shrimp is typically stored in frozen or dehydrated forms [4]. It is processed using various methods, such as steaming and boiling, and the processing efficiency and final quality depend on the type and conditions of the process [5]. Various cooking methods for fish and shrimp, including grilling, curing, frying, and boiling, have been studied for their impact on heavy metals and mineral composition. Studies have shown that changes in cooking methods can be an effective solution for reducing harmful heavy metals and increasing the absorption of beneficial nutrients [6]. Shrimp **is a** source of carotenoids and isoprenoids. Cooking shrimp leads to a reduction in microorganisms, changes in quality characteristics, and affects sensory, physical, thermal, and texture properties (such as moisture content, density, thermal conductivity, volume changes, and shrinkage), resulting in a decrease in production yield (a significant economic factor due to changes in moisture content). In fact, during thermal processing, shrimp proteins undergo denaturation and lose their ability to retain water, which can lead to a reduction in production yield and dimensional changes. Reducing microbial load and decreasing production yield are two important criteria for proper cooking planning for shrimp. Short cooking times and high temperatures result in better-quality products in terms of safety, production speed, and sensory properties. Predicting microbial lethality and the decrease in production yield across various temperature-time combinations provides valuable information for a more informed approach to optimizing the cooking process. These changes are related to the product’s thermal history and its temperature distribution. All of these factors can be estimated and simplified using mathematical models developed to assist the industry in optimizing the thermal processing of shrimp and improving quality [7].

Due to the importance of controlling oil absorption in fried products, several strategies have been proposed to reduce oil absorption, shorten processing time, extend the shelf life of raw materials, and prepare products for delivery to the food industry, restaurants, or households. These strategies include low-pressure frying [8], microwave heating [9], hot air heating, or various pre-treatments such as blanching, coating, freezing [10], or pre-drying [11]. Process modifications can significantly reduce health risks and the degradation of product quality. In recent years, hot air frying has been introduced as an alternative process to deep frying. Hot air frying equipment is available on the market and is evolving [12]. In this method, the product is directly exposed to oil droplets dispersed in hot air, dehydrating the product while the crust gradually forms on its surface [13]. Oil can be added before or during the process with a light coating on the surface of the food to create the desired flavor, texture, and appearance of fried products [14]. Hot air fryers ensure uniform heat transfer between the air and the product being fried [15], resulting in uniform quality changes throughout the product [14]. Ultimately, hot air frying yields a fried product with significantly lower oil content and a moisture level similar to that of deep frying [13]. In hot air frying, the product is heated from all sides simultaneously, and in most cases, there is no need to add oil [12]. Fried products prepared using hot air contain 80% less oil compared to deep frying [16] and result in a 70% energy savings while reducing the discharge of wastewater generated by frying [17].

Therefore, in general, hot air fryers are considered an alternative thermal processing technology for frying foods and a healthier cooking method. Research should also be conducted on the sensory aspects of the product [18]. Comparing the methods of deep frying and hot air frying for different products is important, as the acceptance of the hot air frying process depends on the organoleptic properties of the final product (appearance, crispiness, taste, oily mouthfeel, color, aroma, and overall acceptability) and how closely it resembles deep frying [15]. Consumers are very concerned about fat content, and high fat content reduces product acceptability [19]. Major quality parameters

[DOI: 10.22034/FSCT.22.161.86]

affecting the acceptance of fried products include oil content and texture. Texture and fat content are influenced by processes such as blanching, hot air drying, osmotic pre-treatment, coating (hydrocolloids and starch derivatives), and frying process conditions (temperature, time). Despite the importance of controlling the frying process and improving shrimp product quality, research on frying this seafood product is limited. Furthermore, no studies have been conducted on the hot air frying of shrimp or its comparison with deep frying. There has also been little attention given to heat and mass transfer studies, physical and chemical properties, and nonlinear modeling related to shrimp products and hot air frying processes, nor have such studies been conducted extensively. Given the important role of food processes in the final product's health, increasing awareness of process details such as deep frying and hot air frying will help improve process control, thereby reducing health risks caused by the degradation of various compounds in shrimp consumed by humans. In modern technology, hot air frying ultimately results in a fried product with very low oil content and moisture levels similar to those of deep frying. In this study, transfer phenomena, quality changes in shrimp, and their sensory evaluation during hot air frying were examined.

2-Materials and Methods

2-1-Shrimp Preparation

Fresh and uniformly sized shrimp (*Litopenaeus vannamei*) were purchased from shrimp farms in Gorgan, northern Iran (Bandar Torkaman Industrial Park, Shil Abzi Golestan Company). The shrimp were placed in polyethylene bags and stored in a freezer at subzero temperatures. For sample preparation, the shrimp were kept at room temperature for 10 minutes to thaw. They were first washed and then cut into approximately cylindrical pieces with a diameter of 9 mm and a height of 15 mm for processing.

2-2-Shrimp Frying Process

The shrimp frying process was carried out using two methods: hot air frying (HAF) and deep fat frying (DFF).

2-2-1-Hot Air Frying

The hot air frying process for shrimp was conducted after initial weighing and recording their weight using a laboratory scale with a precision of 0.0001 g (Sartorius GCA803S). A total of 0.01 g of oil was sprayed onto the shrimp pieces, which were then fried at 160°C in a hot air fryer (Geepas-Gaf2708) for 15 minutes. The maximum hot air velocity was 6.5 m/s, measured using a hot wire anemometer (TES 1341). Samples were removed from the fryer at three-minute intervals.

After frying, the shrimp samples were placed on absorbent paper for approximately 2 minutes to remove excess surface oil. Following this, the fried shrimp were weighed and then placed in an oven for moisture content measurement. To ensure uniform conditions for process evaluation, the chemical composition and cross-sectional area of each shrimp piece were assumed to be identical.

2-2-2-Deep Fat Frying

According to Moyano and Pedreschi (2006), after weighing the shrimp and recording their initial weight, the deep-fat frying process was conducted in a fryer (Moulinex Olea Plus). The fryer contained one liter of Oila sunflower oil and was equipped with a temperature controller and a K-type thermocouple. The shrimp were fried at 160°C for 15 minutes [10]. The heating intervals for sample analysis in this method were at 1, 2, 3, 6, 9, 12, and 15 minutes.

2-3- Analysis of Mass Transfer During Frying

To investigate mass transfer phenomena during both deep fat frying and hot air frying of shrimp, the following steps were carried out:

2-3-1- Measurement of Moisture Content

Special metal drying containers were placed in an oven (Memmert UFP500) at 120°C for 20 minutes to remove any residual moisture. After cooling in a desiccator and weighing, the constant weight of the metal containers was determined. Fried shrimp samples were then weighed and dried in a convective oven at 103°C for 16 hours to achieve a constant weight, following the official AOAC method (1995) for moisture measurement in fatty samples. After drying, the container with the sample was transferred to a desiccator using a metal clamp, and once cooled, it was weighed again. The moisture content of the sample was calculated on a dry-weight basis without oil using Equation (1). The experiment was performed in triplicate to ensure accuracy. In this equation, M represents the relative moisture content based on dry weight without oil (g/g, db), W_0 is the constant weight of the metal container, W_1 is the weight of the container with the sample before drying, W_2 is the weight of the container with the sample after drying, and W_{oil} is the weight of absorbed oil based on dry matter (after Soxhlet extraction). All weights were measured in grams (g).

$$M = \frac{W_1 - W_2}{W_2 - W_0 - W_{oil}} \quad (1)$$

2-3-2-Oil Content Measurement in Deep Fat Fried Shrimp

The oil content of deep-fried shrimp was measured over time. The dried samples from the moisture analysis were used to determine oil content using the Soxhlet extraction method with a Soxhlet apparatus (Peco PSU-500), following AOAC standards (2000). The fried and dried shrimp samples were first weighed on filter paper, then completely ground using a porcelain mortar and pestle. The Soxhlet flasks were placed in an oven at 120°C for 20 minutes, followed by cooling in a desiccator to reach a constant weight. A triplicate setup was used for accuracy, with each sample placed in the extractor chamber of the Soxhlet apparatus. Petroleum ether was used as the solvent for oil extraction over a period of 6 hours. The relative oil content was calculated based on dry weight without oil using Equation (2). In this equation, W_{oil} is the absorbed oil content based on dry matter (g/g, db), W_1 is the initial constant weight of the Soxhlet flask, W_2 is the final weight of the Soxhlet flask after extraction and m is the weight of the dried sample without oil. All measurements were expressed in grams (g).

$$W_{oil} = \frac{W_1 - W_2}{m} \quad (2)$$

2-3-3-Estimation of Mass Transfer Parameters

Moisture-time variation data for shrimp during frying were used to estimate mass transfer parameters such as the Biot number, mass transfer coefficient, and moisture diffusivity, similar to the studies by Yildiz et al. (2007) and Sabbaghi et al. (2017) [20, 32]. The shrimp were considered an infinite cylinder. Equation (3) describes the concentration as a function of time and position for an infinite cylinder.

In the following equations, C(x,t) represents the moisture content of the product at any point and time in grams of water per gram of dry matter (g/g, db). C_i is the initial moisture content of the product (g/g, db), and C_∞ is the equilibrium moisture content of the product (moisture content at infinite time) or the moisture content of the processing medium, which can be considered zero. L is the characteristic dimension, equal to half the radius of the shrimp cylinder (in meters), D is the effective diffusivity (m²/s), kc is the mass transfer coefficient (m/s), μ is the root of the non-experimental function for an infinite plate, and t is the time (in seconds). Equation (7) describes the average moisture concentration variation in an infinite cylinder. In Equation (4), $\bar{C}(t)$ represents the average moisture content of the product at time t based on dry matter (g/g, db). Considering the superposition or summation rule, Equation (5) is obtained for the two-dimensional shrimp. By plotting the natural logarithm of concentration variations against time and determining the intercept of the resulting line using Equation (6), the value of μ_1 was obtained. Then, using the slope of this line, the effective diffusivity coefficient (D) was calculated. The dimensionless Biot number for mass transfer (Bi_m) and the mass transfer coefficient (k_c) were also determined using Equation (7).

$$\frac{C(x,t) - C_\infty}{C_i - C_\infty} = \frac{2\sin\mu_n}{\mu_n + \sin\mu_n \cos\mu_n} \times \cos\left(\mu_n \frac{x}{L}\right) \exp\left(-\mu_n^2 \frac{Dt}{L^2}\right) \quad (3)$$

$$\frac{\bar{C}(\mathrm{t}) - C_\infty}{C_i - C_\infty} = \frac{2\sin^2\mu_1}{\mu_1[\mu_1 + \sin\mu_1 \cos\mu_1]} \exp\left(-\mu_1^2 \frac{Dt}{L^2}\right) \quad (4)$$

$$\ln\left(\frac{\bar{C}(\mathrm{t}) - C_\infty}{C_i - C_\infty}\right) = 2\ln E - 2\mu_1^2 \frac{Dt}{L^2} \quad (5)$$

$$E = \frac{2\sin^2\mu_1}{\mu_1[\mu_1 + \sin\mu_1 \cos\mu_1]} \quad (6)$$

[DOI: 10.22034/FSCT.22.161.86]

$$Bi_m = \mu_1 \tan \mu_1 = \frac{k_c L}{D} \quad (7)$$

2-3-4-Investigation of Water Reduction Kinetics

The moisture variation of shrimp during frying follows a decreasing exponential function. The general equation for water loss from the product during frying is given by Equation (8) [21, 22]:

In this equation, K_m represents the specific rate or kinetic constant of water reduction (1/s), which depends on the geometric properties, the initial composition of the product, and processing conditions. m_t and m_∞ represent the moisture content of the product at time t and at infinite time (g/g, db), respectively. By plotting ln $Ln(m_t/m_0)$ against time and determining the slope of the resulting line, K_m was estimated for different experimental temperatures.

$$\ln\left(\frac{m_t - m_\infty}{m_i - m_\infty}\right) = -K_m t \quad (8)$$

2-4-Investigation of Heat Transfer During Frying

2-4-1- Logging Product Temperature Variations

To study the thermal behavior of the frying process, a direct measurement method was used by placing a thermocouple inside the product. A Type-T thermocouple was inserted into the center of the product, which was then fried in both a hot-air fryer and a deep fryer at 160°C. The temperature was maintained using a thermo-controller equipped with a Type-K thermocouple. The temperature variations at the center of the product were recorded for 15 minutes at 1-second intervals using a data logger (Model TC-08 “RS-232” by Pico Technology) and PicoLog software on a computer. This experiment was repeated three times, and the average recorded central temperature curves were analyzed.

2-4-2- Estimation of Thermal Properties of Shrimp

According to Hanan Hamid et al. (2018), the thermal conductivity (k) and specific heat capacity (c_p) of shrimp were estimated as functions of five different sample compositions (moisture, protein, fat, ash, and carbohydrate content) using Equation (9) and Equation (10), respectively. The variations of these properties over time during the process were also analyzed [23]. Protein content was measured using the Kjeldahl method with a Kjeltec device (Behr InKjel 625P) and a conversion factor of 6.25 (AOAC, 1996). Ash content was determined using an electric furnace (Nabertherm B510) at 550°C (AOAC, 1996). All measurements were conducted in triplicate, and the results were reported on a wet basis. In the following equations, x_w is the moisture content (g/g, wb), x_{pr} is the protein content (g/g, wb), x_f is the fat content (g/g, wb), x_c is the carbohydrate content (g/g, wb), x_{ash} is the ash content (g/g, wb), k is the thermal conductivity (W/m·K) and C_p is the specific heat capacity (J/kg·K). The thermal diffusivity (m²/**s**) of shrimp was calculated using Equation (11)**.**

$$k = 0/58x_w + 0/155x_{pr} + 0/16x_f + 0/25x_c + 0/135x_{ash} \quad (9)$$

$$\alpha = \frac{k}{\rho c_p}$$

$$C_p = 4187x_w + 1549x_{pr} + 1675x_f + 1424x_c + 837x_{ash}$$

(10)

(11)

2-4-3-Estimation of Convective Heat Transfer Coefficient Using Core Temperature

The convective heat transfer coefficient was estimated by solving equations for one-dimensional heat conduction in Cartesian coordinates, according to Equation (12).

The shrimp was modeled as a finite cylinder, which can be approximated as the intersection of an infinite plate and an infinite cylinder. Under this assumption, the unaccomplished temperature fraction for the finite case is the product of the temperature fractions of the two infinite geometries, as given in Equation (13). According to Equation (14), following Sabbaghi et al. (2017), by plotting the natural logarithm of the unaccomplished temperature fraction against process time, the slope of the linear portion of the curve is given $-2\mu_1^2\frac{\alpha t}{L^2}$ [32]. Since thermal diffusivity and half of the shrimp cylinder radius are known, μ_1 can be calculated. Finally, using Equation (15), the dimensionless Biot number for heat transfer and the convective heat transfer coefficient can be estimated. In these equations, T(r, t) is the product temperature at any point and time, T_i is the initial product temperature, T_∞ is the processing medium temperature (°C), L is half of the shrimp cylinder radius (m), α is the thermal diffusivity (m²/s), h is the convective heat transfer coefficient (W/m².°C), μ is the root of the non-experimental function for an infinite cylinder and t is the time (s).

$$\frac{\partial^2 T}{\partial x^2}=\frac{1}{\alpha}\frac{\partial T}{\partial t},\quad 0\le x\le L \quad \text{for } t>0 \tag{12}$$

$$\left(\frac{T(r,z,t)-T_\infty}{T_i-T_\infty}\right)_{\text{finite plate}}=\left(\frac{T(r,t)-T_\infty}{T_i-T_\infty}\right)_{\text{infinite cylinder}}\times\left(\frac{T(z,t)-T_\infty}{T_i-T_\infty}\right)_{\text{infinite plate}} \tag{13}$$

$$\ln\left(\frac{T(r,z,t)-T_\infty}{T_i-T_\infty}\right)=\ln A-2\mu_1^2\frac{\alpha t}{L^2} \tag{14}$$

$$Bi_h=\mu_1\tan\mu_1=\frac{hL}{k} \tag{15}$$

3-Results and Discussion

3-1-Results of Chemical Composition and Thermal Properties of Shrimp

The results of the analysis of water, protein, fat, ash, dry matter, and carbohydrates in whiteleg shrimp are presented in Table 1. These findings are consistent with USDA data (1996).

Table 1. Amount of shrimp chemical compounds

Chemical compounds	Amount (unit)
Protein	**12.25(%)***
Fat	**1(%)***
Ash	**1.75 (%)***
Moisture	**85 (%)**
Dry matter	**15 (%)***
Carbohydrate	**Negligible**

* Based on wet weight

3-2- Results of Mass Transfer Analysis During Hot Air Frying

3-2-1-Moisture Changes

[DOI: 10.22034/FSCT.22.161.86]

Figure 1 illustrates the changes in shrimp moisture content during hot-air frying and deep frying, along with the standard deviation of experimental data as a function of processing time. At the beginning of the hot-air frying process, the moisture reduction rate increases until the surface moisture has completely evaporated. As the product loses moisture, the rate of moisture change gradually stabilizes. As expected, once the shrimp temperature reaches the boiling point of water, evaporation occurs, happening more rapidly at higher frying temperatures. The intensity of this evaporation is more pronounced during the first three minutes of the process due to the sudden evaporation of free surface moisture and the temperature difference between the shrimp's internal moisture and the boiling point of water. During hot-air frying, the partial vapor pressure difference between the product and the hot air causes water evaporation. This pressure difference is naturally higher at the beginning of the process. These observations align with the findings of several researchers [10, 22, 25, 26, 27].

As evident, the rate of moisture change during deep frying is such that after one minute of frying, the moisture content of the product reaches approximately 2 g per gram of dry matter. The moisture loss in shrimp during deep frying is so intense that after nine minutes, the moisture content of the product approaches zero, whereas this phenomenon was not observed in hot-air frying. Pan et al. (2015) observed a similar trend in shrimp moisture reduction during vacuum frying, where higher temperatures led to greater water loss over time [27]. Yang et al. (2021), in their study on shrimp frying, noted that post-frying moisture content was influenced by the frying medium. The moisture transfer mechanism in shrimp occurs from the center toward the outer layers due to capillary pressure and pressure gradients. Once the temperature reaches the boiling point of water, evaporation takes place through molecular diffusion [28]. Costa et al. (1999) stated that during frying, the rate of water loss increases until surface drying is complete and then decreases as frying time progresses [29]. Farkas and Hubbard (2000), as well as Sabbaghi et al. (2015), reported that the maximum rate of moisture loss occurs during the initial stages of the frying process [30, 31].

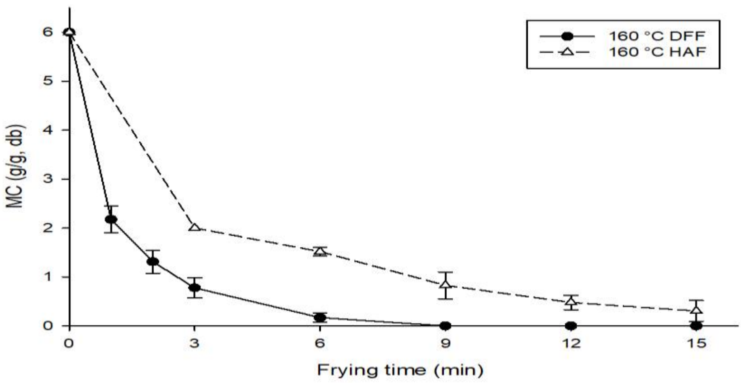

Fig 1. Moisture content during deep fat frying (DFF) and hot air frying (HAF)

ey did not
describe a regular pattern for Biot number variations

3-2-2-Mass Transfer Parameters

Figure 2 illustrates the variations in the dimensionless average concentration over frying time using hot-air frying and deep fat frying methods. This diagram was used to calculate mass transfer parameters, including the Biot number, mass transfer coefficient, and effective moisture diffusivity. As observed, the rate of water loss in shrimp was higher in deep-fat frying than in hot-air frying. The obtained variations, as shown in Table 2, for mass transfer parameters are consistent with the

[20]. With a decrease in the moisture loss rate, the mass transfer coefficient systematically decreased. The effective diffusivity in deep-fat frying was higher than in hot-air frying. Sabbaghi et al. (2017) stated that with an increase in process temperature, the Biot number, mass transfer coefficient, and effective moisture diffusivity significantly increase [32].

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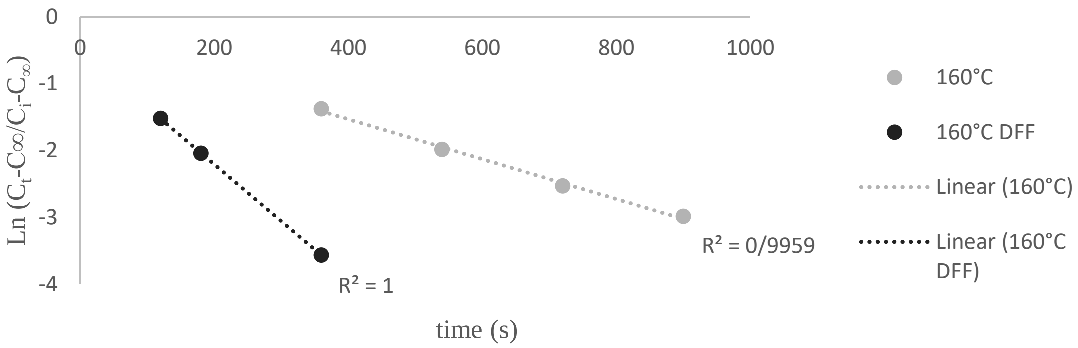

Fig 2. Mean concentration over time during deep fat frying (DFF) and hot air frying (HAF)

Table ۲. Mass transfer parameters for deep fat frying (DFF) and hot air frying (HAF)

Effective penetration coefficient ($D\times10^{-9}$ m^2/s)	Mass transfer coefficient ($K_c\times10^{-5}m/s$)	Biot number (Bi_m)	Temperature (°C)
۲/۸۲	۰/۶۹	۳/55	HAF۱۶۰
۹/۱۹	۱/۴۵	5/55	DFF ۱۶۰

3-2-3-Kinetics of Water Loss from the Product

In Figure 3, for fitting the kinetic model to the natural logarithm of dimensionless moisture content, the intercept was assumed to be zero. The moisture changes in the product during frying followed a decreasing exponential function. The kinetic model for moisture reduction during frying was derived by Krokida et al. (2001) as a function [22]. By calculating the slope of the fitted lines on the natural logarithm of dimensionless moisture data, the kinetic constant for water loss (K_m) in hot air frying at 160°C was determined as 0.0033 ± 0.0007 s^{-1}. Similarly, for deep frying, the kinetic constant was calculated as 0.0098 ± 0.0020 s^{-1}, which was significantly higher than that of hot air frying. As expected, at 160°C, the kinetic constant for water loss in deep frying was significantly greater than in hot air frying. Mohebbi et al. (2011) stated that the final moisture content of the product decreases with an increase in frying temperature, and with prolonged frying time, the water loss rate becomes limited [33]. Debnath et al. (2003) also indicated that the kinetic constant for water loss increases with rising process temperature [11]. Similarly, Romani et al. (2008) reported that approximately three minutes after the frying process begins, the water loss rate follows a decreasing and nearly stable trend [34].

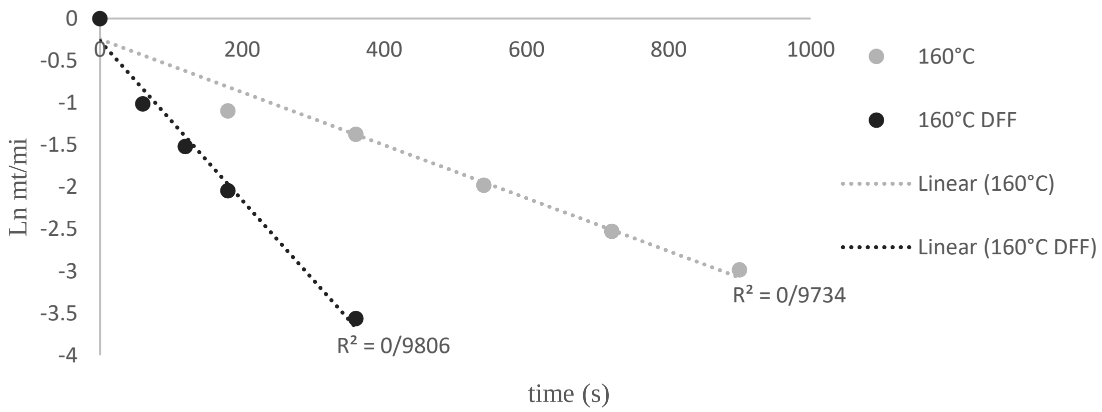

Fig 3. The natural logarithm of dimensionless moisture over time

3-2-4-Oil Absorption in Shrimp During Deep Frying

Figure 4 presents the variations in oil absorption by shrimp over frying time. The changes in oil absorption during deep frying followed an approximately linear increase. Significant oil uptake in the deep-frying process occurred through two mechanisms: condensation of water vapor inside the food and capillary flow. In the initial stages of frying, water vapor was expelled from the product's tissue due to internal pressure, resulting in lower oil absorption. As frying time increased and evaporation progressed, the hydrophilic properties of the product gradually diminished. Consequently, due to capillary action, the likelihood of oil penetration into the pores increased. Upon removing the shrimp from the hot oil, the temperature and pressure drop led to a suction effect caused by vapor condensation inside the pores, drawing surface oil into the shrimp’s internal structure. Additionally, the extent of oil penetration depended on oil viscosity and the structure of the product’s pores. Higher viscosity caused more oil to remain on the surface, reducing deep penetration. Oil absorption was deeper when pores were smaller with a lower radius, as increased capillary pressure facilitated oil migration. After nine minutes of frying, when the product was fully dried and steam was no longer present, oil absorption occurred primarily due to direct contact with the hot oil. Given the linear relationship between the kinetic constants of moisture loss and oil absorption, applying pre-treatments such as drying, which reduces the kinetic constant of moisture loss and decreases porosity, can effectively limit oil absorption. Farkas et al. (1996) stated that as long as the product's core temperature remains around 100°C, the rate of oil migration into the product is minimal. In other words, as long as intense evaporation occurs, the outward movement of water vapor prevents oil from penetrating the food structure, effectively halting oil migration. Since these two mass transfer flows occur in opposite directions, and considering the wetting and hydrophilic properties of the product, shrimp does not readily absorb oil [35].

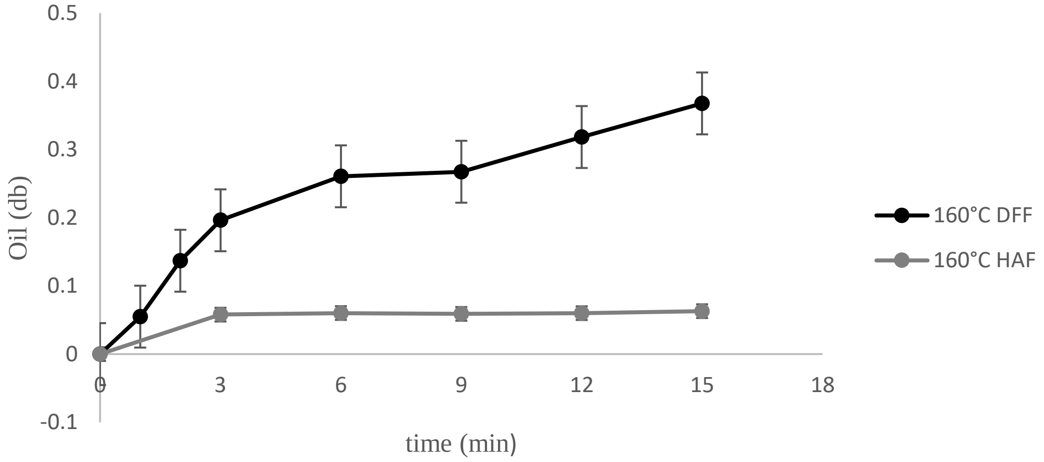

Fig 4. Oil content during deep fat frying (DFF) and hot air frying (HAF) over time

3-3-Results of Heat Transfer Analysis During Frying

3-3-1- Changes in the Central Temperature of Shrimp

Figure 5 illustrates the variations in the central temperature of shrimp during hot air frying and deep fat frying. Temperature changes were recorded using a thermocouple. The temperature sensors, in a laboratory-scale setup, were connected to a computer via a data logger to record temperature variations throughout the process. The product temperature was recorded in two ways: as a function of time (kinetics) and as a function of position within the product (profile). In the hot air frying method, the central temperature of the product reached the boiling point of water and remained constant for a period. Upon reaching the boiling point, the increased vapor pressure due to evaporation and the entrapment of steam bubbles within the product led to an increase in the boiling point, following thermodynamic principles. As the evaporation rate decreased during the boiling phase, the boiling point dropped but remained slightly above 100°C due to the presence of dissolved components. In deep fat frying, due to the high heat transfer rate of oil, the central temperature of the product reached the boiling point of water more quickly and remained constant for a while. Eventually, after the surface

[DOI: 10.22034/FSCT.22.161.86]

water had evaporated and a crust had formed, the temperature approached that of the oil. In hot air frying, the central temperature of the product remained nearly constant after reaching the boiling point of water until the end of the process. The observed variations in the core temperature of the product during frying align with the findings of many researchers [31, 32]. Farkas et al. (1996) stated that during frying, heat transfer occurs in the presence of two thermal sinks [35]. The first thermal sink involves sensible heat, which increases the product's temperature from its initial state to the boiling point of water. This thermal sink gradually becomes limited as frying progresses and the product's core temperature reaches the boiling point. The second thermal sink pertains to latent heat, which drives water evaporation at the crust/core interface, where water transitions into steam and remains throughout the frying process. Sahin et al. (1999) reported that the higher the process temperature, the shorter the constant-temperature phase (100°C) in the thermal kinetics curve of the product, and the product temperature rises more rapidly toward the oil temperature [36]. This phenomenon was particularly evident in deep fat frying in the present study. Nguyen et al. (2019) stated that during shrimp drying, the shrimp's temperature increased rapidly within the first 15 minutes of hot air drying and approached the medium's temperature [4].

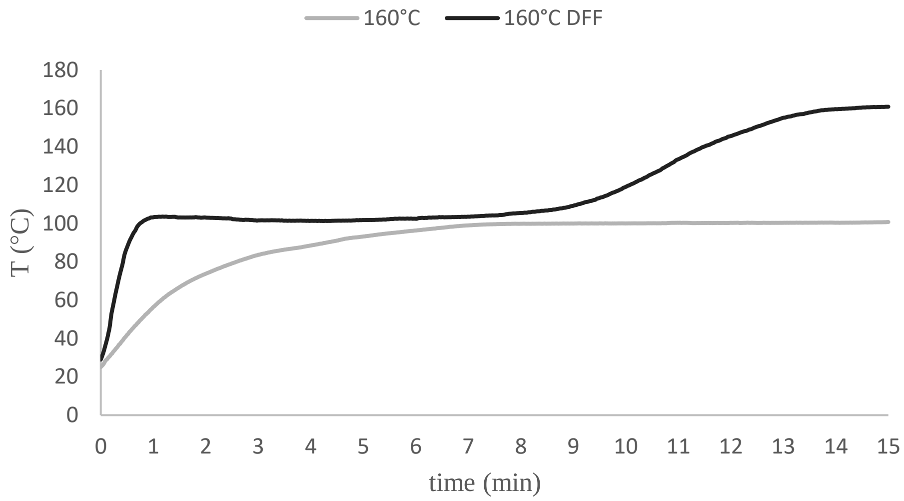

Fig ۵. The Central temperature changes during deep fat frying (DFF) and hot air frying (HAF)

3-3-2-Convective Heat Transfer Coefficient Estimation Using Central Temperature

Figure 6 illustrates the linear portion of the natural logarithm of the dimensionless temperature versus frying time for hot air frying. Similarly, Figure 7 presents these variations for deep frying. The downward trend in these graphs indicates that the heating rate of shrimp, based on its central temperature, decreases as the frying process progresses. By utilizing the slope of the linear section of the logarithmic plot of the dimensionless temperature versus time and considering the known physical and thermal properties of shrimp (density: 1080 kg/m^3, thermal conductivity: 0.5158 J/mol·s·K, specific heat capacity: 3780 J/kg·K, and thermal diffusivity: 1.26×10^{-7} m^2/s), the Biot number for heat transfer (Bi_h) was determined. Consequently, the convective heat transfer coefficient was estimated based on the central temperature. Table 4 presents the estimated heat transfer parameters during hot air frying and deep frying for shrimp. The convective heat transfer coefficient in deep frying was higher than in hot air frying, primarily due to steam bubble formation, increased turbulence, and oil degradation during frying. The convective heat transfer coefficient plays a crucial role in developing sensory attributes and browning of the product. Assuming that the energy required for moisture evaporation remains constant, an increase in the moisture removal rate would result in a greater portion of the input energy being allocated to the evaporation process. This reduces the energy available for increasing internal energy, thereby decreasing the convective heat transfer coefficient at lower temperatures. This finding aligns with the results of Costa et al. (1999), Sahin et al. (1999), and Budzaki and Seruga (2004) [29, 36, 37], but it contradicts the findings of Yildiz et al. (2007) [20]. To explain the higher heat transfer coefficient in deep frying, Costa et al. (1999) reported that nucleate boiling occurs during frying.

[DOI: 10.22034/FSCT.22.161.86]

In this process, steam bubbles form at different surfaces of the product and ascend toward the upper layers of the oil. The movement of steam bubbles after formation at the surface significantly impacts the turbulence and flow disturbance of the oil, which in turn increases the convective heat transfer coefficient [29]. Nguyen et al. (2019) observed similar heat transfer coefficient values during shrimp drying with hot air [4].

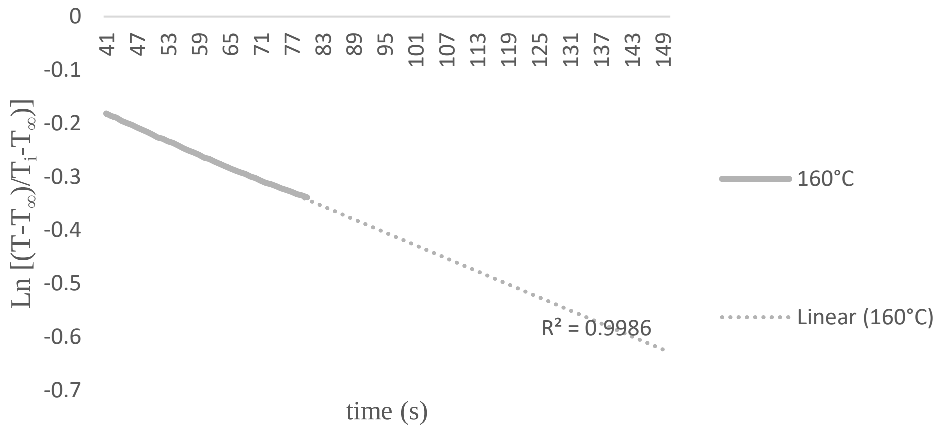

Fig ۶. The natural logarithm of dimensionless temperature against time during HAF

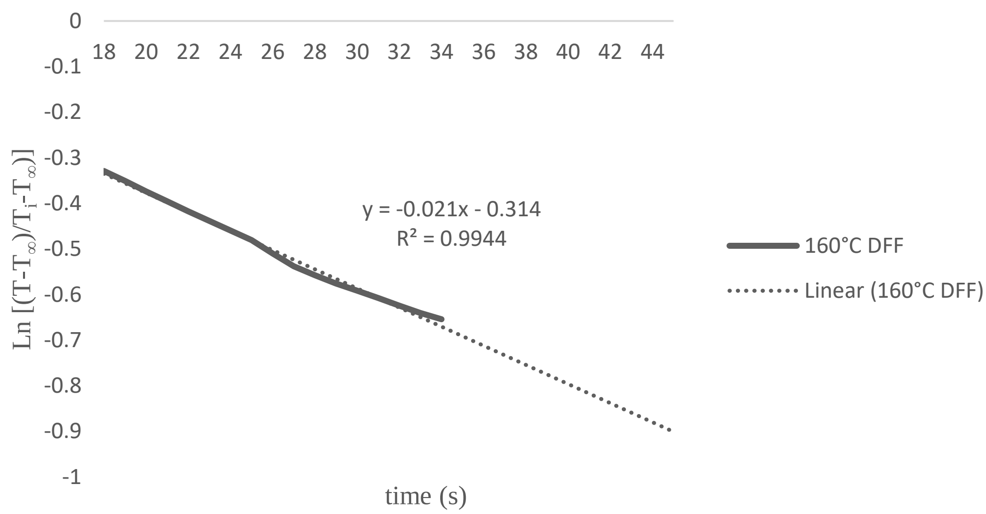

Fig ۷. The natural logarithm of dimensionless temperature against time during DFF

Table ۳. Heat transfer parameters for deep fat frying (DFF) and hot air frying (HAF)

Displacement heat transfer coefficient (W/m² °C)	Biot number (Bi_h)	Temperature (°C)
19/42	۰/084	**HAF۱۶۰**
113/15	۰/493	**DFF ۱۶۰**

[DOI: 10.22034/FSCT.22.161.86]

4-Conclusion

In this study, mass and heat transfer parameters during hot air frying of shrimp were estimated. These estimations were based on the measurement of dimensionless moisture and its dependence on time. The obtained values for hot air frying were lower than those for deep frying. In deep frying, the Biot number and effective diffusivity were higher than in hot air frying. The highest moisture reduction kinetic constant was observed in deep frying. As frying time increased, the rate of moisture loss gradually decreased. The intensity of moisture removal in deep frying was significantly higher than in hot air frying. In this study, after 9 minutes of deep frying, the shrimp's moisture content reached nearly zero, whereas in hot air frying, a zero moisture level was not observed even after 15 minutes. The oil content of shrimp in deep frying increased almost linearly over 15 minutes, indicating high oil absorption in shrimp, whereas hot air frying could limit this oil uptake. During deep frying, after the internal moisture was depleted, the product's core temperature rapidly approached the oil temperature. If the process is not properly controlled, this can lead to the degradation of beneficial and health-promoting compounds in shrimp, ultimately reducing its nutritional value. Conversely, in hot air frying, the core temperature changes were more controlled, which could help preserve the product's health benefits.

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[DOI: 10.22034/FSCT.22.161.86]

مجله علوم و صنایع غذایی ایران

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مقاله علمی_پژوهشی

آنالیز انتقال حرارت و جرم طی فرآیند سرخ کردن هوای داغ و سرخ کردن عمیق میگو

بهاره معروف پور[1]، امان محمد ضیائی فر[2*]، محمد قربانی[3]، حسن صباغی[4]، سعید یلقی[5]

۱ دانشجوی دکتری علوم و مهندسی صنایع غذایی، دانشگاه علوم کشاورزی و منابع طبیعی گرگان، گرگان، ایران

۲* استاد گروه مهندسی صنایع غذایی، دانشگاه علوم کشاورزی و منابع طبیعی گرگان، گرگان، ایران

۳ استاد گروه شیمی مواد غذایی، دانشگاه علوم کشاورزی و منابع طبیعی گرگان، گرگان، ایران

۴استادیار گروه علوم و مهندسی مواد غذایی، دانشکده کشاورزی و دامپروری، مجتمع آموزش عالی تربت جام، خراسان رضوی، ایران

۵استادیار گروه شیلات، مرکز تحقیقات شیلات استان گلستان، گرگان، ایران

اطلاعات مقاله

تاریخ های مقاله :

تاریخ دریافت: ۱۴۰۲/۹/۸

تاریخ پذیرش: ۱۴۰۳/۲/۲۳

کلمات کلیدی:

میگو،

سرخ‌کردن هوای داغ،

انتقال جرم،

انتقال حرارت

DOI: 10.22034/FSCT.22.161.86.

* مسئول مکاتبات:

ziaiifar@gau.ac.ir

چکیده

در این پژوهش پدیده‌های انتقال طی سرخ‌کردن با هوای داغ و سرخ کردن عمیق بررسی شد. عملیات سرخ‌کردن با هوای داغ (HAF) و سرخ‌کردن عمیق (DFF) در دمای °C ۱۶۰ به مدت ۱۵ دقیقه برای قطعات استوانه‌ای میگو انجام گرفت. تغییرات دمای مرکزی محصول طی سرخ‌کردن با استفاده از ترموکوپل نوع T متصل به دستگاه ثبت داده در رایانه ثبت گردید. محتوی رطوبت و روغن نمونه‌ها در هر زمان از فرایند اندازه‌گیری شد. پارامترهای انتقال حرارت و جرم با استفاده از نمودارهای نسبت‌های دمایی و غلظت بدون بعد و معادلات تجربی برآورد شد. نتایج نشان داد که پارامترهای انتقال جرم و حرات طی سرخ‌کردن با هوای داغ کمتر از روش سرخ‌کردن عمیق هستند. در سرخ کردن عمیق عدد بایوت و ضریب نفوذ موثر بالاتر از روش سرخ کردن هوای داغ بود. ثابت سینتیکی کاهش رطوبت در محصول در روش سرخ کردن عمیق بیشتر بود.