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KINETICS OF COLOR AND PHYSICAL ATTRIBUTES OF COOKIE DURING DEEP-FAT FRYING BY IMAGE PROCESSING TECHNIQUES

MOHAMMAD R. ABDOLLAHI MOGHADDAM[1], ALI RAFE[2,3] and MASOUD TAGHIZADEH[1]

[1]Department of Food Science and Technology, Ferdowsi University of Mashhad (FUM), PO Box 91775-1163, Mashhad, Iran
[2]Research Institute of Food Science and Technology, PO Box 91735-147, Mashhad, Iran

[3]Corresponding author.
TEL: +98-511-5425385;
FAX: +98-511-5003150;
EMAIL: a.rafe@rifst.ac.ir

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ABSTRACT

Deep-fat frying is one of the most prevail methods of food processing, which affect color and physical properties. The effects of frying temperature (150–180C) and time on the physical characteristics of cookie, including crust thickness, internal porosity, color and hardness, have been investigated. Kinetics of color and physical attributes of cookie were investigated using zero/first order of kinetics. Crust color was also evaluated and L^*, a^*, b^* and ΔE, values were obtained. Further, rheological property of crust surface, i.e., hardness was examined. Hardness and L^*, followed a first-order change, while the other parameters had zero-order kinetics. The temperature dependence of reaction's constants explained by the Arrhenius equation and activation energy was found to be in the range of 21.2–92.86 kJ/mol. The L^*, crust thickness and ΔE had higher correlations with texture than internal porosity, which suggests that L^* can reliably be used to predict the hardness of deep-fat fried cookie.

PRACTICAL APPLICATION

The physical properties of cookie such as color and texture have so important for consumers of food products. Since, texture measurement during processing is a time-consuming and destructive technique, finding another method for its evaluating will be beneficial. Therefore, the correlation between color and texture of cookie during deep-fat frying by applying image processing techniques was investigated. It was found a good correlation for L^* and ΔE with texture than internal porosity. The activation energy of internal porosity was lowest of all the physical properties. It seems the L^* can be reliably used to predict the hardness of deep-fat fried cookie. Therefore, by having enough knowledge on surface color of cookie, it will be possible to estimate texture properties.

INTRODUCTION

Bezhy is a kind of popular frying cookie, which is widely consumed as a snack with breakfast in the western regions of Iran. It is prepared in free-form style dough composed of refined wheat flour, sugar, fresh cow milk and vegetable oil, which are fried by deep-fat frying. In order to understand the processing steps, optimization, quality control and designation of large-scale production line, the details of cookie preparation process must be investigated.

Deep-fat frying is an integral part of Bezhy preparation. The conditions in deep-fat frying lead to high heat and mass transfer rates, rapid cooking, surface browning, texture and flavor development (Pedreschi *et al.* 2006). On the other hand, simultaneous heat and mass transfer occurs in a fairly short time during frying, which results in countered flow of water vapor and oil at the surface of the food, and physicochemical changes of major food components. It is supposed that in the process of water evaporation, volume expansion of water leads to the porous structure characterized by voids in the interior and crevices, crack and fine pores in the crust of batter, as reported for chickpea batter fried into boondi (Bhat and Bhattacharya 2001). Some kinetic studies of food quality changes such as surface color

and texture during deep-fat frying have been carried out (Ateba and Mittal 1994; Baik and Mittal 2003; Nourian and Ramaswamy 2003a; Kumar *et al.* 2006). Two typical phenomena, i.e., protein denaturation and starch gelatinization happen during the frying of product. The surface browning of food during deep-fat frying is due to the nonenzymatic browning reactions, known as the Maillard reaction, and could be mathematically modeled by zero or first-order kinetics (Labuza 1984).

Some of important quality attributes of fried food products are texture, porosity, color, taste and nutrition (Dogan *et al.* 2005). Among the different physical properties of food, color is considered the most important visual attribute in the perception of the product quality, which directly affects the consumer preference. In other words, the color of the food surface is almost the first quality parameter evaluated by consumers and is critical in the acceptance of the product, even before it enters into the mouth (Ziaiifar *et al.* 2008). Consumers tend to associate color with texture, flavor, safety, storage time, nutrition and the level of satisfaction because of the fact that it correlates well with physical, chemical and sensorial evaluations of food quality. Along with the color, texture, also, plays an important role in overall acceptance of food quality by consumers. Changes in textural properties, including texture profile analyzer (TPA) and crust color of wheat flour base donuts were measured during deep-fat frying at 180, 190 and 200C. Crust color changes were fitted to kinetics of first order, and the activation energy was calculated (Velez-Ruiz and Sosa-Morales 2003). There has also been an increasing interest in studying the microstructural properties of foods such as porosity and pore size distribution because of their importance in defining the food quality and the better understanding of the transport properties of foods, which leads to the production of porous foods or foods with low density. As deep-fat frying of cookie develops, typical brown color and uniform porous texture are required to reach to a good quality product. The product with a uniform light brown color and fine porous texture gains a high degree of acceptance by consumers. An under-fried batter offers a raw taste along with soggy texture, while an over-fried product is associated with a crisp texture but lacks attractive appearance and juicy mouthfeel. Therefore, having detailed information on color and textural parameters during deep-fat frying of Bezhy would be useful in predicting the changes in quality during frying, thereby enabling better process control and improving in the appearance through optimization of the processing parameters. In addition, many studies (Duizer 2001; Fillion and Kilcast 2002; Baixauli *et al.* 2003; Ross and Scanlon 2004; Vincent 2004; Pedreschi and Moyano 2005) have focused on the texture of fried foods since textural parameters such as crispness are of great interest to consumers. Hence, scope exists to study the changes in Cookie batters with particular reference to quality attributes as appearance, color and texture that can happen during frying. The structure of food is related to quality changes experienced during food processing such as frying (Mellema 2003; Donald 2004; Adedeji and Ngadi 2010). It is also interesting to note that a liquid-like batter material attains a hard solid-like texture during frying of traditional foods like boondi (Bhat and Bhattacharya 2001) and jilebi (Chakkaravarthi *et al.* 2009) though the aspects of frying batter are less investigated topics.

In recent years, computer vision (CV) analysis, computerized image processing and analyzing systems, as a rapid, nondestructive and low-cost means have gained many interesting applications in food industry. It is also amenable to industrial online applications, and baking process can be monitored by this technique (Paquet-Durand *et al.* 2012). This method has been successfully applied for identification and quality evaluation (Gerrard *et al.* 1996; Abdullah *et al.* 2004; Brosnan and Sun 2004; Du and Sun 2004, 2006; Qiao *et al.* 2004, 2005; Pace *et al.* 2011; Shafiee *et al.* 2013), grading and sorting of fruits and vegetables, meat and fish and bakery products (Mendoza and Aguilera 2004; Blasco *et al.* 2009; Zapotoczny 2011), as well as detection and segmentation of surface defects (Bennedsen *et al.* 2005; Munkevik *et al.* 2007; Dammer *et al.* 2011; Ataş *et al.* 2012). Some reviews of recent developments in image processing for food quality assessments have been published (Brosnan and Sun 2004; Du and Sun 2006; Zheng *et al.* 2006). Image processing has the advantage of providing reproducible color measurements and allows the characterizing of both macro- and microstructural aspects of foods (Dziezak 1988; Riva and Liviero 2000). Therefore, the main objectives of the present study were (1) to investigate the effect of frying temperature and time on crust thickness, internal porosity, surface color and textural properties of Bezhy, and (2) to measure the kinetics of their changes during frying of Bezhy, in order to determine the kinetic parameters in terms of reaction rate constant and activation energy.

MATERIALS AND METHODS

Sample Preparation

Refined wheat flour (Rosha, Takmakaron Co, Karaj, Iran), refined sunflower oil (Nina co, Mashhad, Iran), sugar (Bargah, Sourosh Bargah Toos Co, Mashhad, Iran) and fresh cow milk (Pegah Co, Mashhad, Iran) were purchased from a local supermarket. Prior to mixing, the sunflower oil was preheated and then, was properly mixed with refined wheat flour in the ratio 1:7 (w/w). Fresh cow milk was heated in an open steam jacketed kettle with constant stirring until boiling point. The sugar was dissolved in boiled milk in the

TABLE 1. PROXIMATE CHEMICAL COMPOSITION OF UNFRIED BEZHY DOUGH

Constituent	g/100 g
Moisture	11.70
Fat	20.40
Protein	6.30
Ash (minerals)	0.53
Carbohydrates	61.12

ratio 1:1.5 (w/v). The aforementioned solution and the mixture of oil and flour were properly blended to obtain homogeneous dough. The dough was prepared fresh each time. It shaped into rectangular dough with about $8 \times 2 \times 1$ cm size to carry out the frying experiments. The chemical composition of unfried dough is given in Table 1.

Deep-Fat Frying

Bezhy dough samples were fried in an electric deep-fat fryer (ZDF-2500, Suzuki Z.F., Shizuoka, Japan) at three different temperatures of 150, 165 and 180C. Samples were withdrawn at regular intervals of 60 s in period of 8 min. Frying times and temperatures were chosen on the basis of preliminary experiments focused on colorimetric measurements, in order to obtain and compare products with different color degrees (under- and over-fried products). Temperature was recorded by using a thermometer inserted on the centre of the oil bath, and the temperature of oil was controlled up to a deviation of ±3C by the circulation of oil. Prior to starting frying, the refined sunflower oil was preheated in the fryer to the predetermined temperatures. After being fried, the samples were drained (10 s) and gently wiped with tissue paper to remove loosely adhering oil and then, were cooled to room temperature and packed in polyethylene bags. Bezhy dough samples were fried at predetermined time and temperature and all the experiments were carried out in two replicates. Since, Bezhy is a kind of popular frying cookie in some regions of Iran and in order to have better understanding its color, a typical picture of Bezhy at 165C was provided in Fig. 1.

Image Acquisition and Processing

The CV used for image acquisition and processing for studying the kinetics of surface color and internal porosity changes of Bezhy fried at different times and oil temperatures was composed of the following components and steps: (1) Four fluorescent lamps (Opple, 8 W, model: MX396-Y82; 60 cm length, Hunilux Lighting Co., Budapest, Hungary) was located in a wooden box with black internal walls illuminating the samples. The lamps were 45 cm above the sample and at an angle of 90° with the sample plane to give a uniform light intensity over it. The color digital camera (Canon EOS 1000D, Tokyo, Japan) was located in the box vertically above the sample and at a distance of 25 cm from it. A schematic view of the image acquisition system was shown in Fig. 2. The calibration or white balance of the imaging system was performed by fluorescence H. The other camera setting was manual AF mode, aperture value F5.6, lens focal length 24 mm, shutter speed 1.25 s and ISO speed 100. The images captured by the mentioned camera with resolution (2272×1704 pixels) were

FIG. 1. THE FRIED BEZHY COOKIE (165C, 8 MIN), THE CROSS SECTION (A) AND THE SURFACE SECTION (B)

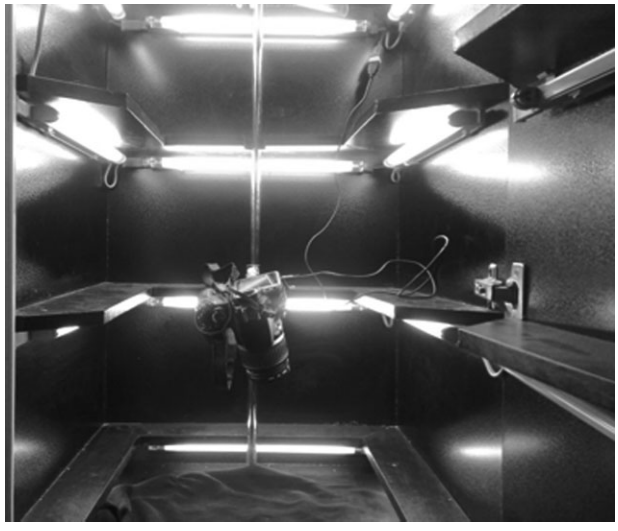

FIG. 2. A SCHEMATIC VIEW OF THE IMAGE ACQUISITION SYSTEM

saved on a computer with software (Canon Utilities Zoom Browzer EX Version 6.1.1) in JPEG format.

(2) Image preprocessing: Before analyzing the digital images, their quality had to be improved. So, to remove the noise of the images and to enhance their contrast by the Image J software (National Institutes Health, Bethesda, MD), median filter was used.

(3) Segmentation: The preprocessed images were segmented and separated from the black background using the Photoshop software (Adobe Photoshop, V8, New York, NY).

(4) Color space conversion: The RGB images were converted into $L^*a^*b^*$ units using the Image J software, and data were obtained through the software in terms of L^* (lightness, ranging from zero [black] to 100 [white]), a^* (ranging from +60 [red] to −60 [green]) and b^* (ranging from +60 [yellow] to −60 [blue]). The total color change (ΔE) was calculated by the following equation:

$$\Delta E = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2} \quad (1)$$

where, subscripts 1 and 2 are before and after frying parameters, respectively.

(5) Measuring the internal porosity percentage of samples. The samples were cut along their longitudinal plane and the Image J was used to measure their internal porosity percentage.

As for each specified temperature and time, two samples were used to apply image analysis, and the other two samples were used to measure the internal porosity percentage, so the mean values of the measured $L^*a^*b^*$ and internal porosity were reported.

Texture Measurement

Textural properties of samples were measured by subjecting them to a TPA test using texture analyzer (Model QTS Brookfield, Engineering Laboratories, Harlow, UK) equipped with 25 kg load cell. Data were analyzed by using Texture Expert Exceed Software supplied along with the instrument. Samples resized to $2 \times 2 \times 1.5$ cm were subjected to a two-cycle compression–decompression test up to 75% total compression using a rectangular probe with 4×4 cm size at a crosshead speed of 1 mm per second (Guarda *et al.* 2004). Penetration test was also carried out by using a circular probe with 2 mm, which was penetrated with the rate of 1 mm/s. From the force–deformation curve, texture parameters namely hardness, chewiness and cohesiveness were measured. For each specified temperature and time, two samples were used to measure texture parameters, and the mean values of the measured texture parameters of samples were reported.

Kinetic Considerations

The kinetic evaluation of reactions involves the study of the rates and mechanisms. To analyze the general quality changes in foodstuffs, the following approach is generally applied (Singh 1994):

$$\pm\frac{dQ}{dt} = kQ^n \quad (2)$$

where, Q is the quality attribute, k is rate constant, n is the order of reaction and t is time (min).

For the majority of foodstuffs, the time dependence relationships appear to be described by zero- or first-order models (Chen and Ramaswamy 2002). In zero-order reactions, the relationship between quality attribute and time is linear and therefore by substituting $n = 0$ in Eq. (2), the following equation is achieved:

$$-\frac{dQ}{dt} = k \quad (3)$$

Eq. (3) can be integrated to obtain

$$Q = Q_0 - kt \quad (4)$$

In the first-order reactions, the relationship between quality attribute and time is exponential and therefore substituting $n = 1$, Eq. (2) gives

$$-\frac{dQ}{dt} = kQ \quad (5)$$

Upon the integration has been done, we get

$$ln\frac{Q}{Q_0} = -kt \quad (6)$$

The rate constant is generally temperature dependent and the relationship can be modeled on an Arrhenius relationship:

$$k = k_0 \exp\left(-\frac{E_a}{RT}\right) \quad (7)$$

where, k is rate constant (dimensionless), k_0 is the pre-exponential factor, E_a is the activation energy (kJ/mol), R is gas constant (8.314 J/kmol) and T is the absolute temperature (K).

The accuracy of fit is evaluated by calculating the root mean square percent error (RMS %) as follows:

$$RMS\% = \sqrt{1\Big/ n\left(\sum_1^n\left(\frac{Q_{exp} - Q_{cal}}{Q_{exp}}\right)^2\right)} * 100 \quad (8)$$

where, Q_{exp} is the experimental value and Q_{cal} is the calculated value. The extent of suitability of models was reported in terms of correlation coefficients (R^2) and the significance of R values was examined at ($P < 0.01$).

RESULTS AND DISCUSSION

Crust Color: Lightness (L^*)

The crust lightness changes during deep-fat frying of Bezhy are illustrated in Fig. 3. The L^* value decreased as the frying time increased. The initial L^* value was 86.30, 78.81 and 75.28 at 150, 165 and 180C, respectively. It was gradually decreased to 72.85, 37.98 and 38.98 depending on the temperature of the treatment. As it can be seen, there was small change in L^* at 150C, and a drastic change was occurred at 180C. Additionally, the reaction followed first-order kinetics ($n = 1$). The Arrhenius plot for lightness changes during frying of Bezhy at different temperature is shown in Fig. 4. The R^2 and RMS values between the experimental and predicted data were well within the limits of experimental error, and are presented in Table 2. The activation energy was found to be 92.86 kJ/mol for the crust lightness change during the deep-fat frying of Bezhy. It is much higher than that of Gulabjamun ($E_a = 43.52$ kJ/mol, Kumar *et al.* 2006), tofu ($E_a = 76.0$ kJ/mol, Baik and Mittal 2003), meat balls ($E_a = 16.92$ kJ/mol, Ateba and Mittal 1994) and wheat flour-based donuts ($E_a = 18.2$ kJ/mol, Velez-Ruiz and Sosa-Morales 2003). The differences may be attributed to the different compositions and reactions involved, implying darkening of the Bezhy crust. The decrease in the lightness value may also be attributed to Maillard reaction and caramelization of lactose at high temperatures, which is in accordance with L^* changes in other fried products

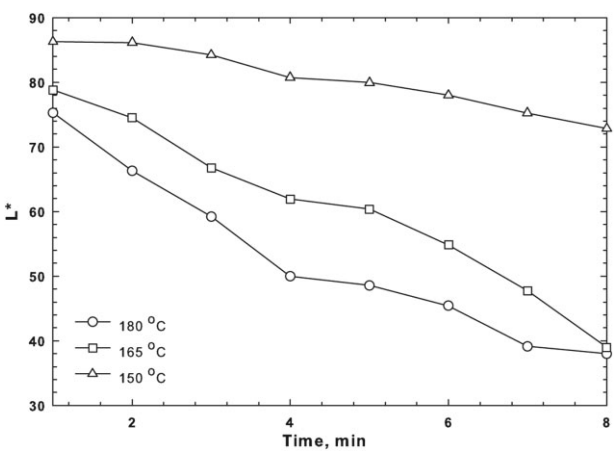

FIG. 3. CHANGES IN THE LIGHTNESS (L^*) OF BEZHY CRUST DURING FRYING AT DIFFERENT TIME-TEMPERATURES

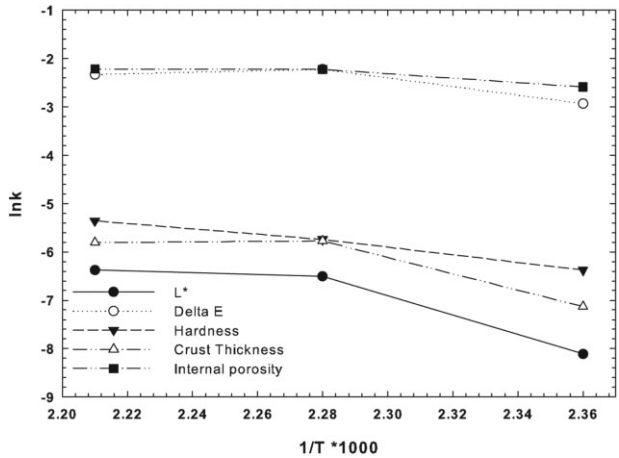

FIG. 4. ARRHENIUS PLOTS OF RATE CONSTANTS FOR COLOR CHANGES OF BEZHY DURING FRYING

(Martins *et al.* 2001; Velez-Ruiz and Sosa-Morales 2003; Hwang *et al.* 2009). The rates of both reactions depend on the product composition and chemical conditions. However, the most significant factor affecting the reaction rate is temperature (Tan and Mittal 2006). Generally, the E_a of enzymatic browning has been reported as 105–210 kJ/mol (Saguy and Karel 1980), which is more than the values of frying-induced browning. However, the value obtained in this work (92.86 kJ/mol) is within the values (37–167 kJ/mol) reported for the nonenzymatic browning (Villota and Hawkes 1992).

Crust Color: Total Color (ΔE)

Total color of the crust determined using Eq. (1), which increased during frying of Bezhy as shown in Fig. 5. The increase in ΔE with time was rapid at the beginning of the process, and at higher temperatures reached to higher values. The maximum total color values were recorded 50.16–54.27 depending on the treatment temperature and time combination. The total color of Bezhy was lower than Gulabjamun ball, which may be related to the difference in chemical composition. The reaction kinetics followed the zero order and the relevant Arrhenius plot was provided in Fig. 4. The R^2 and RMS values indicate that the Arrhenius model has achieved the highest correlation (Table 2). E_a for ΔE was 32.55 kJ/mol, which was lower than that of L^*. The increase in ΔE reflecting darkening of the crust could be attributed to the Maillard browning and caramelization of milk sugar in Bezhy. However, the relative amounts of melanoidins in Bezhy at different stages of frying could not be same. The extent of browning reactions is affected by many factors such as temperature, time, pH, water activity and state of food system, which apparently keep changing during the frying process.

TABLE 2. THE COLOR AND TEXTURE KINETICS OF BEZHY DURING DEEP-FAT FRYING

Order of reaction	Parameter	E_a (kJ/mol)	K_o	R^2	RMS%
First	L^*	92.86	1.15×10^8	0.82	0.58
Zero	ΔE	32.55	6.36×10^2	0.64	0.33
Zero	Crust thickness	74.78	1.6×10^6	0.76	0.53
First	Hardness	56.53	1.65×10^4	0.99	0.007
Zero	Internal porosity	21.20	31.79	0.80	0.0013

Crust Thickness

The change of crust thickness during frying of Bezhy was provided in Fig. 6. The crust thickness increased as frying time/temperature was increased, whereas the crust thickness was 0.55 mm at 150C and increased to 1.41 mm at 180C. Thus, crust thickness of Bezhy was greatly influenced by temperature. In fact, the amount of water exhausted from the product during frying was a determining factor in crust thickness (Mariscal and Bouchon 2008). The maximum thickness during frying of Bezhy at temperature range 150–180C happened at 8 and 3 min time, respectively. This behavior was also reported in the previous work (Sahin and Sumnu 2009). The reaction kinetics followed the zero order and the relevant Arrhenius plot has been included in Fig. 4. The activation energy was obtained 74.78 kJ/mol, which was more than that for ΔE but less than L^*. The relevant R^2 and RMS values have also been presented in Table 2, which indicates high performance of the developed model.

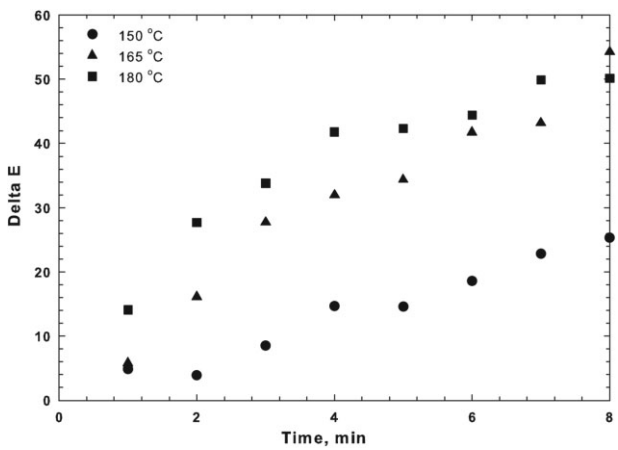

FIG. 5. CHANGES IN THE TOTAL COLOR (ΔE) OF BEZHY CRUST DURING FRYING AT DIFFERENT TIME-TEMPERATURES

Texture Kinetics of Bezhy during Frying

The changes in the hardness of Bezhy as a function of time and temperature have been shown in Fig. 7. It can be seen that the hardness value increased with time in proportion to the frying temperature; since higher temperature caused faster moisture loss from the surface of the dough resulting in more hardness. Thus, the process of crust formation appeared to be accelerated at higher frying temperatures. However, a little decrease in hardness at 165C at 4 to 7 min times was observed. The initial hardness value was 0.53 N/mm, which increased to 1.11, 1.91 and 1.95 N/mm at 150, 165 and 180C, respectively. These changes could be best

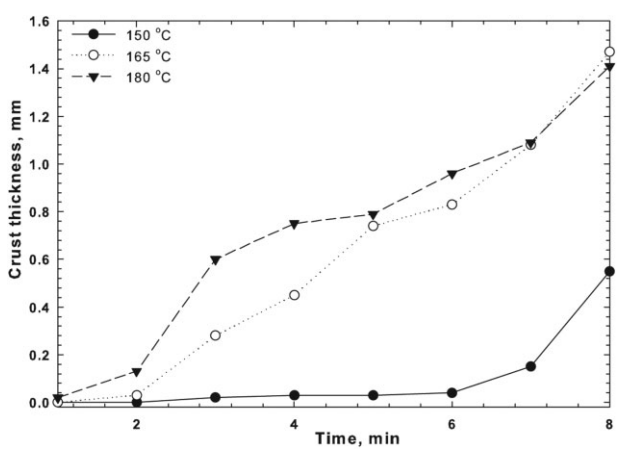

FIG. 6. CHANGES OF CRUST THICKNESS OF BEZHY DURING FRYING AT DIFFERENT TEMPERATURES

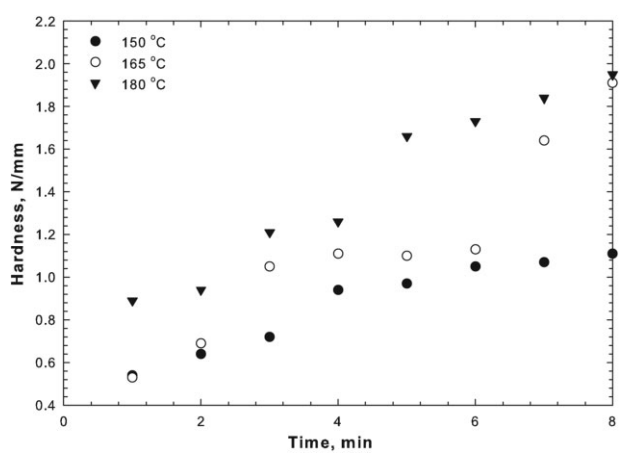

FIG. 7. CHANGES IN THE HARDNESS OF BEZHY DURING FRYING AT DIFFERENT TIME-TEMPERATURES

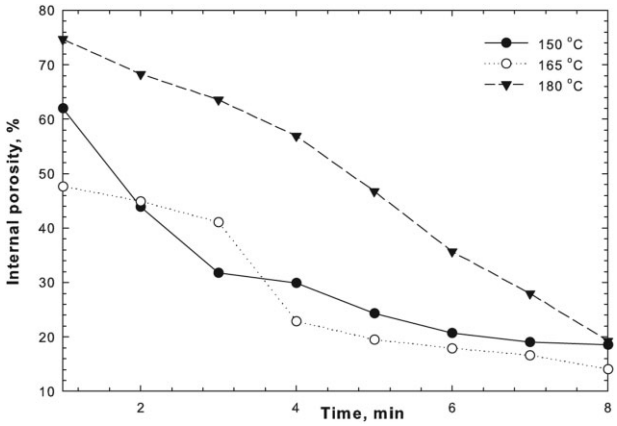

FIG. 8. THE INTERNAL POROSITY VALUES DURING DEEP-FAT FRYING OF BEZHY AT DIFFERENT TEMPERATURES

explained by first-order kinetics. The Arrhenius plot for hardness change during frying of Bezhy has been illustrated in Fig. 4. The R^2 and RMS values between the experimental and predicted data were well within the limits of experimental error and are given in Table 2. The E_a of frying-induced increase in hardness was 56.53 kJ/mol during the frying of Bezhy.

Internal Porosity during Frying

The internal porosity changes during the deep-fat frying of Bezhy at different temperatures were shown in Fig. 8. It could be seen that, by increasing temperature, internal porosity of Bezhy was increased. However, there were little differences in the values of internal porosity between temperature 150 and 165C. The internal porosity value decreased with time in proportion to the frying temperature, which may be attributed to faster moisture loss from the dough as time of frying proceed. The activation energy was obtained 21.20 kJ/mol, which was the lowest value of all E_a for all the parameters measured in our study. The R^2 and RMS values were presented in Table 2, which indicated the best fitness of model.

Correlations between Hardness, Crust Thickness, Internal Porosity and Color Parameters

The changes of hardness, crust thickness, internal porosity and color parameters of Bezhy were affected by the frying process exhibiting definite correlations. The correlation matrix was presented in Table 3, which indicated L^* value and porosity were negatively correlated with hardness ($P < 0.01$), and crust thickness and total color were directly correlated ($P < 0.01$) with hardness. Thus, the increasing surface darkening as reflected in the decreasing of L^* value was accompanied by increasing rigidity (measured as hardness) of the Bezhy. It can be found the total color and crust thickness also increased in parallel with the hardness of Bezhy. This showed that the development of crust color was hand-in-hand with the structure development seen in the hardening of Bezhy. Similar relationships were observed in tofu and gulabjamun balls during frying (Baik and Mittal 2003; Nourian and Ramaswamy 2003a,b; Kumar *et al.* 2006). In addition, it may be noted that the L^*, crust thickness and ΔE have higher correlations with texture than internal porosity, which indicates that L^* can reliably be used to predict the hardness of deep-fat fried Bezhy. The same results were also obtained in gulabjamun balls to correlate the color parameters with texture (Kumar *et al.* 2006). Although crust thickness and ΔE can also be used for prediction, the determination of L^* was faster and easier than these factors. Therefore, it was suggested to use L^* value for estimation of hardness of Bezhy or similar dough products during frying and can be applied in food frying operations.

CONCLUSION

Kinetics of color, crust thickness, porosity and texture development during the deep-fat frying process involved in Bezhy preparation were measured by using classical reaction orders and Arrhenius relationship. The L^* decreased, while ΔE, crust thickness, internal porosity and hardness increased during deep-fat frying. The browning-induced changes in color parameter L^* and hardness parameters were described by first-order reaction, while the other parameters had zero-order kinetics. The activation energy of these physical parameters ranged from 21.20 to 91.86 kJ/mol for temperatures between 150 and 180C. The increase in hardness as a result of frying could be described by first-order kinetics. The activation energy of internal porosity was the lowest of all the studied physical properties. The color changes were highly correlated with the hardness of Bezhy, the L^* and the total color (ΔE) exhibiting a high correlation coefficient with the hardness, porosity and crust

TABLE 3. CORRELATIONS BETWEEN HARDNESS, INTERNAL POROSITY, CRUST THICKNESS AND COLOR PARAMETERS OF DEEP-FAT FRIED BEZHY

	Hardness	Crust thickness	Internal porosity	L^*	ΔE
Hardness	1				
Crust thickness	0.92	1			
Internal porosity	–0.40	–0.42	1		
L^*	–0.92	–0.95	0.26	1	
ΔE	0.92	0.94	–0.35	–0.97	1

thickness. The results could potentially be used for predicting the quality change of Bezhy during deep-fat frying, in order to be applied in food frying operations and industries.

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