Japan Journal of Food Engineering, Vol. 6, No. 2, pp. 143 - 148, Jun. 2005

◇◇◇ **Original Paper** ◇◇◇

Oil Absorption and Drying in the Deep Fat Frying Process of Wheat Flour - Water Mixture, from Batter to Dough

Pariya THANATUKSORN[1], Chidphong PRADISTSUWANA[2], Pantipa JANTAWAT[2]
and Toru SUZUKI[1†]

[1]*Department of Food Science and Technology, Tokyo University of Marine Science and Technology,*
4-5-7 Konan, Minato-ku, Tokyo, 108-8477 Japan
[2]*Department of Food Technology, Faculty of Science, Chulalongkorn University, Bangkok, Thailand*

The effect of initial moisture content on oil absorption was investigated for a food model composed of various wheat flour and water mixtures. The models were prepared by widely varying the initial moisture content between 40% and 80% (wet basis), which covers dough to batter. The samples were then fried at 150°C in palm olein oil for 1 to 7 min. The results revealed that both oil absorption and moisture loss have a linear relation with the square root of the frying time. It was suggested that the initial moisture content affected the porous structure forming through starch gelatinization during the frying process, consequently which induced the increase of absorbed oil during the frying process.

Key words: initial moisture content, oil absorption, gelatinization, porous structure

1. Introduction

Deep fat frying is the most popular unit operation in the world because this process provides unique flavor and crisp texture [1]. The high oil content in fried products is recognized as causing health problems. Many research works on oil absorption have revealed that a number of factors such as initial moisture content, frying time and temperature, frying oil quality and composition, porosity, cooling time, and surface area significantly affect the amount of oil in fried foods [1,2]. However, this involvement is still not clearly understood.

As a food material undergoes frying, both chemical and physical changes take place such as starch gelatinization, protein denaturation, water vaporization, and crust formation [3]. The movement of water as vapor form causes higher porosity. The formation of pores due to water evaporation allows the oil to penetrate the voids [4]. Several research works have reported that oil penetrates samples to replace the evaporated water. Gamble et al. [5] found a relationship between moisture loss and oil uptake during the frying of potato slices; both transfer phenomena were expressed as the linear functions of the square root of the frying time. Moreira et al. [6] stated that higher initial moisture content in tortilla chips resulted in final higher oil uptake. Krokida et al. [7] found that the oil content in French fries decreases as the time for pre-drying increases.

Although oil absorption studies have been widely conducted, most research concerns potato products. On the other hand, there are few reports on the oil-absorption mechanism in batter products. Baker and Scott-Kline [8] used a high-protein batter containing egg albumen to improve the texture and functional properties of breaded fried chicken parts. Mohamed et al. [9] studied the effect of protein from different sources on the quality and oil absorption characteristics of frying batters, and concluded that the addition of ovalbumin reduces oil absorption, while the addition of egg yolk increases the oil absorption. Mohamed et al. [10] pointed out that increasing the initial water in the rice flour batter model leads to a reduction in viscosity, greater porosity and more oil absorption. Shih and Daigle [11] found that batters containing rice flour as the main component produced a better oil-resistant coating. Altunakar et al. [12] also pointed out that adding pregelatinized tapioca starch to chicken nugget coating reduced the oil content.

Many studies have been conducted to find out the effect of initial moisture content (IMC) on oil uptake targeting particular fried products, but the moisture content has been limited to a narrow range. Therefore, the objective of this study is to investigate the effect of a wide range, focusing on IMC in oil uptake and/or the moisture

---

(Received 12 Apr. 2005; accepted 9 May. 2005)

† Fax: 03-5463-0585 E-mail: toru@s.kaiyodai.ac.jp

loss during frying, i.e. from potato to batter. Oil uptake and structure alteration affected by IMC are also discussed.

2. Materials and Methods

2.1 Materials and sample preparation

The model samples were prepared using commercial wheat flour whose approximate composition was 8% protein and 0.2% fat (United Flour Mill Co. Ltd., Thailand) at initial moisture levels of 40%, 60%, 70% and 80% (wet basis), i.e. 66.67%, 150%, 233.33%, and 400% in dry basis. These levels were achieved by mixing the flour with distilled water at room temperature (30°C) for 15 min. Because the 40% sample had the consistency of dough, it was reformed between two rolls (150-mm Deluxe, Atlas) until it reached a final thickness of 0.8 mm. The sample was later cut by a circular stainless steel mold into a 5-cm diameter circular disk, weighing 3.00 ± 0.05 g. The three batter-like samples, consisting of 60%, 70% and 80% moisture levels, were weighed at 4.50 ± 0.05, 6.00 ± 0.05 and 9.00 ± 0.05 g, respectively, into Teflon-coated circular molds, as shown in Figure 1. The weights of these samples were strategically chosen so that they would contain equal quantities of wheat-flour.

All four samples were then deep fat fried in an oil bath (Thermo-mate BF600, Yamato, Japan) containing 3L of palm olein oil (Thai Olene Co. Ltd., Thailand) at 150°C for 1, 3, 5, and 7 min, respectively. The fried samples were left to cool for 0, 1, 3, and 6 min, respectively. Preliminary tests indicated that there were no significant differences in the amount of free fatty acid in the frying oil when it was used for less than three hours. Therefore, the oil used in this study was discarded after three hours of frying.

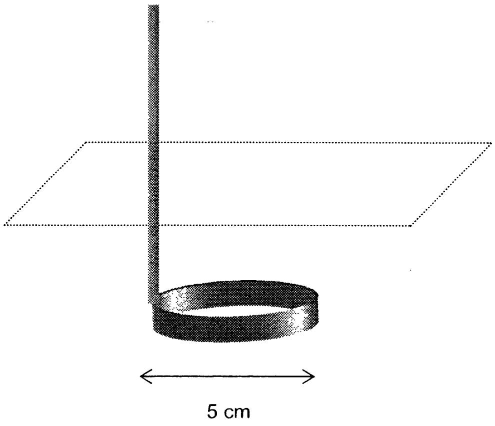


Fig. 1 Teflon coated circular mold used for frying the 60%, 70% and 80% model.

2.2 Measurement of oil and moisture content

After frying and cooling, the samples were immediately dipped in a beaker containing 100 mL of petroleum ether for 2 s to remove the oil adhering to the surface. Southern et al. [13] previously used this method for the same purpose. The net oil absorbed by the samples was determined by soxhlet extraction [14]. The residual moisture content in the samples was determined in a hot air oven at 105°C for 12 h or until the sample weight was constant [14]. The residual moisture and the oil content of samples were based on the dried and defatted sample weight. Two replicates were used for all experiments.

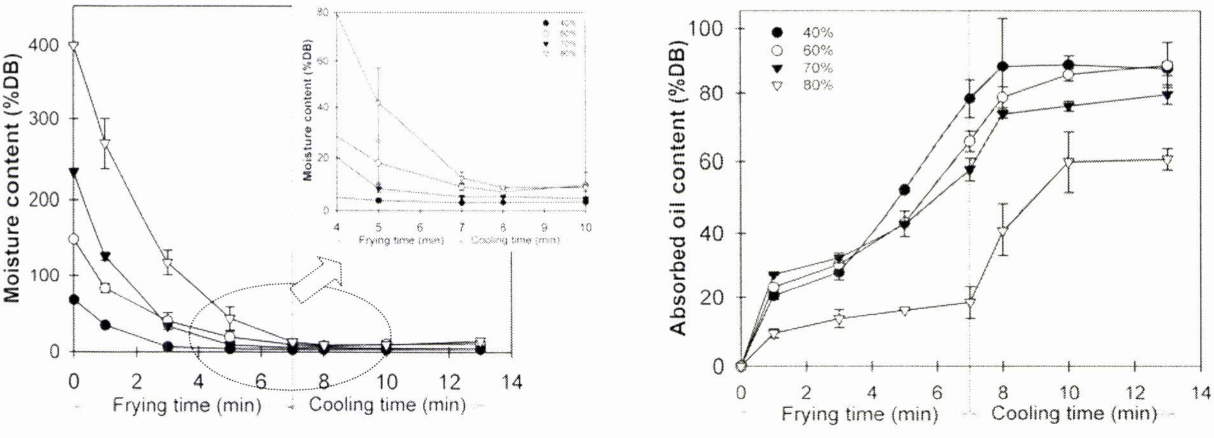
2.3 Observation of the microstructure

The samples with all four initial moisture contents were fried in oil at 150°C for 7 min. After the respective frying times, the samples were immediately dipped in petroleum ether for 24 h to draw the oil from the samples. The defatted samples were dried and mounted on stubs with a commercial conductive adhesive. The cross-sectional surface of the sliced samples was observed using a Scanning Electron Microscope (JSM-5410LV, JEOL Japan) with an accelerating voltage of 15 kV.

3. Results

The effect of IMC on moisture loss during the frying and subsequent cooling process is shown in Fig. 2a. In the frying process, moisture loss rapidly occurred in the first 3 min of frying, and gradually declined as the frying time increased. Toward the end of frying, the residual moisture content in the samples containing 40, 60, and 70% in the initial moisture was not different ($p \le 0.05$), while the residual moisture content for the 80% IMC sample was slightly higher at the end of frying compared to the others.

It has been reported that oil absorption takes place in both the frying and the cooling period [15,16]. Thus, in this study, the amount of net oil absorbed during the frying process was determined independently by removing the oil located at the sample surface just after removal from the frying oil. Figure 2b shows the effect of IMC on the absorbed oil content during frying. The absorbed oil of all samples increased as the frying time increased. In the first 1–3 min of frying, the absorbed oil for the 40, 60, and 70% IMC samples was slightly different; however, that for the 80% IMC sample was at a considerably low level. Once the frying period finishes (post-frying), the absorbed oil in all samples sharply increases in the first few minutes of cooling time. This provides evidence for



(a) (b)

Fig. 2 The changes of absorbed oil and moisture content for wheat flour-water mixture containing 40–80% moisture during frying and cooling process.

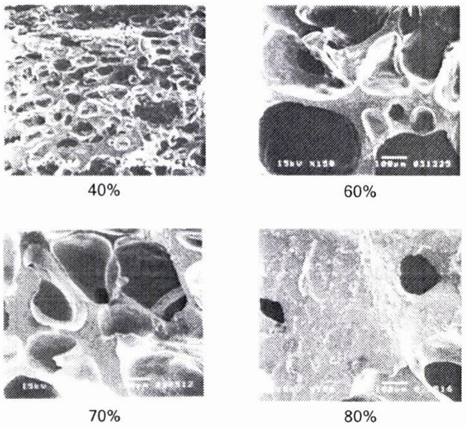


Fig. 3 SEM photos of cross-section wheat flour models prepared with different initial moisture content at 7 min of frying.

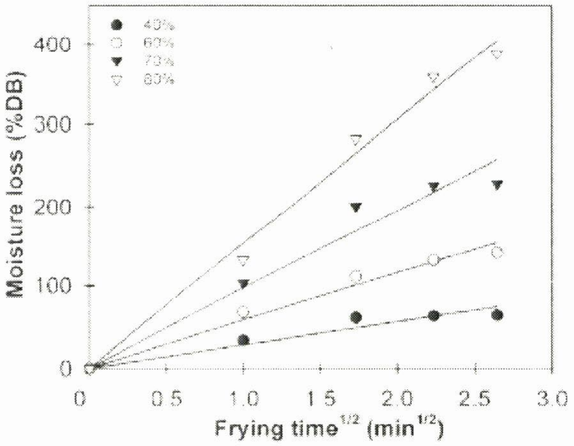


Fig. 4 Relationship between moisture loss and square root of frying time for the samples with initial moisture content of 40–80% initial moisture content.

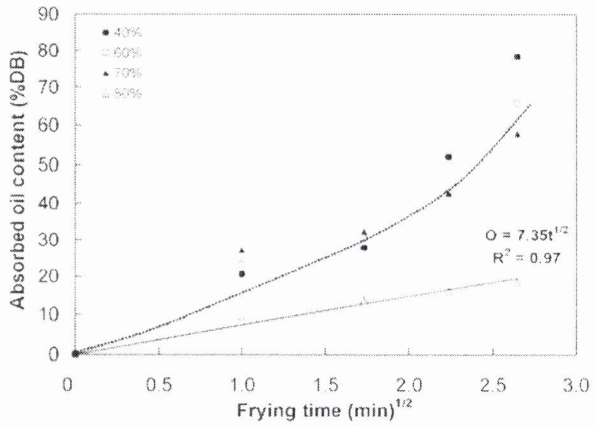


Fig. 5 The relation of absorbed oil and the square root of frying time for the samples with initial moisture content of 40–80% initial moisture content.

the suggestion by Gamble and Rice [17] that the oil on the sample surface is sucked into pores due to force caused by vacuum pressure.

Microscope observation confirmed that varying the IMC influenced sample microstructure. Figure 3 shows the microstructure images of 7-min-fried samples with different IMC observed by SEM. The structure of the IMC 40% sample was a sponge-like network, which had many small pores due to the rapid evaporation of the water inside. The 60% and 70% IMC samples showed a few large pores. For the 80% IMC sample, a small number of pores were observed throughout the frying process. That is, its structure had the fewest pores.

4. Discussion

Gamble and Rice [5] found that both the amount of moisture loss and oil absorption in potato chips are a function of the square root of the frying time. In our study, plotting moisture loss and absorbed oil content as the function of the square root of the frying time has been

Table 1 Moisture fraction and absorbed oil as the function of the square root of the frying time.

Combination	Equation	Correlation (R^2)
Moisture fraction		
40%	$M_L/M_O = 0.47\ t^{1/2}$	0.98
60%		
70%		
80%	$M_L/M_O = 0.38\ t^{1/2}$	0.98
Absorbed oil content		
40%	-	-
60%	-	-
70%	-	-
80%	$O = 7.35\ t^{1/2}$	0.97

attempted, as shown in Figs. 4 and 5, respectively. It was found that the moisture loss of all samples was linear to the square root of the frying time. The explanation of plotting in this from and related equation will be discussed in the below paragraph.

As shown in Fig. 5, the oil absorption of only 80% IMC sample indicates a linear correlation with the square root of the frying time, the same as the moisture loss. Their approximate correlation equations are also listed in Table 1. The oil absorption process of the 40–70% IMC samples clearly appeared to be on the same curve. However, the oil absorption process in the 80% IMC sample showed a different tendency, indicating a low absorption level.

Mittelman et al. [19] also proposed, through mathematical considerations of mass transfer, that the drying process during frying for thin slab potato tissue shows the square root dependency of the frying time as Eq. (1).

$$M_L / M_O = \frac{K}{a} D^{1/2} t^{1/2} \tag{1}$$

where M_L = integration of evaporated water, M_O = initial moisture, K = proportionality constant, a = half-thickness of the slab, D = diffusivity of water in the tissue, and t = the time elapsed since the beginning of evaporation. Herein, to normalize the data from the samples with different initial moisture levels, the relationship between the ratio of moisture loss to initial moisture content, and the square root of the frying time were replotted in Fig. 6. The ratios of normalized moisture loss for all IMC samples were also confirmed to have a linear correlation with the square root of the frying time approximately up to M_L/M_O = 0.8. Furthermore, it was found that the plots of 40, 60 and 70% IMC samples, except of 80%, concentrated almost on the same line (R^2 = 0.98). Although the 80% sample showed an alternative line, there seems no large difference compared with those in oil absorption. The equations representing moisture and oil absorption vs. the square root of the frying time are shown in Table 1. Although the parameters in the obtained equations are not discussed in detail, these results suggest that a difference in IMC does not significantly affect the rate of moisture loss during frying. The mechanism of moisture loss in the deep fat frying process has often been described by the moisture diffusion-limited process [20]. In this case, the microstructure of the sample should influence the diffusivity coefficient. That is, the effective diffusivity increases with increasing porosity and pore size [21]. Marousis and Saravacos [22] reported that the development of channels during drying increases the effective moisture diffusivity, facilitating the transport of water vapor from the interior to the surface of the sample. As shown in our results, however, despite the microstructure observed by SEM showed considerable difference among different IMC samples, the rate of moisture loss in the different IMC samples was similar, and almost independent of the difference in their microstructures. Thus, it can be considered that moisture loss during frying is not a water diffusion-limited process, as has been suggested by previous researchers [20], but it may be governed by the heat transfer mechanism, including the latent heat of evaporation or gelatinization.

The relationship between the rate of oil absorption and moisture loss was plotted as shown in Fig. 7. In the case of the 40–70% IMC samples, the rate of oil absorption was inversely proportional to the rate of moisture loss, and more, their relationship in the 40, 60, and 70% samples showed a similar tendency. That is, reducing the moisture loss causes an increase in oil penetration. On the other hand, the plot for the 80% sample indicates a linear relation (R^2 = 0.88) in a wide moisture range, which has a minus gradient slope.

The variation in IMC affects the degree of gelatinization ability in starchy foods and consequently governs the formation of structure. Usually, the water-to-starch ratio plays an important role in the degree of starch gelatinization. Starch gelatinizes completely in general when the water-to-starch ratio is higher than 2:1 (weight by weight) [18], even though it depends on the kind of starch. So, the amount of water in the 40–70% samples was insufficient for gelatinization of starch or rapidly evaporated during frying, leading to the incomplete formation of starch gel and greater porosity. Therefore, on the frying process in the 40–70% samples, the steam pressure inside the samples could be considered to control the impeding of oil penetration. On the other hand, for the 80% sample, the

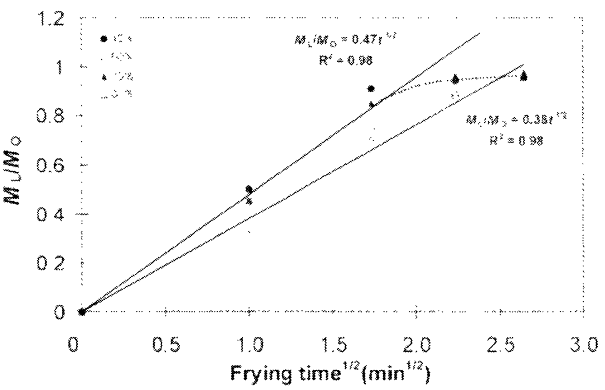


Fig. 6 Relationship between fraction of moisture loss and the square root of frying time for the samples with initial moisture content of 40–80% initial moisture content.

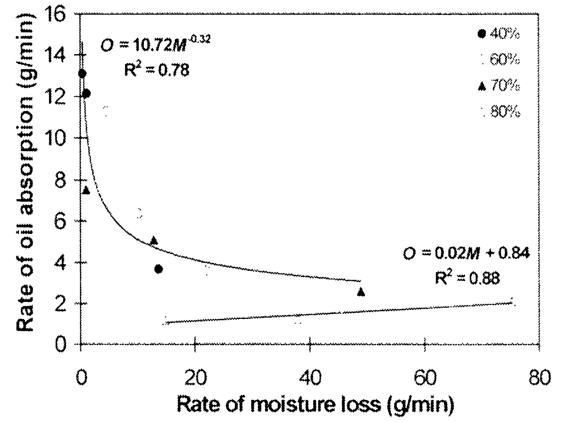


Fig. 7 Correlation between rate of moisture loss and oil absorption time for the samples with initial moisture content of 40–80% initial moisture content.

amount of water was thought sufficient to completely form starch gel without migration of moisture according to water demand model by Watanabe [23], so that the fried product of 80% IMC would have fewer pores due to high water demand of starch gelatinization. Its structure retarded water loss due to evaporation because the gelatinized starch molecules hold many water molecules, and acted as a film that prevented the oil entering the sample. These discussion which make a correlate between oil absorption and starch gelatinization were based on the assumption from literature, however, it may necessary to investigate the corresponding with the actual gelatinization data for our used sample.

5. Conclusions

This study on a wide range of IMC in wheat flour and water mixtures revealed that the initial moisture probobly affects starch gelatinization in the frying process, and consequently, structural changes affect the oil absorption in the final fried sample. That is, it was found the there is a critical IMC for the oil absorption mechanism, from 70 to 80%, which influences alteration in the sample structure due to starch gelatinization. Furthermore, the drying process during the frying of starchy food is not always a diffusion-limited process, but the moisture held due to starch gelatinization plays an important role in completing the drying process. The data about gelatinization of starch in the varying IMC were not shown in this study, however, the information from the other published literature elucidated that the 80% IMC sample was sufficient to be completely gelatinized. In order to get a concrete conclusion, the data for gelatinization is now being gathered.

6. Acknowledgment

The authors would like to thank the Thailand-Japan Technology Transfer Project (TJTTP-OECF) and the Office of Academic Affairs, Chulalongkorn University (Thailand) for funding this reserch.

References

[1] R. G. Moreira, M. E. Castell-Perez, M. A. Barrufat; Deep-fat Frying: Fundamentals and Applications, Publishers, Aspen, Maryland, 1999.

[2] I. S. Saguy, E. J. Pinthus; Oil uptake during deep fat frying: Factors and mechanism. Food Technol., **49**, 142–145, 152 (1995).

[3] R. P. Singh; Heat and mass transfer in foods during deep fat frying. Food Technol., **49**, 134–137 (1995).

[4] I. S. Saguy, D. Dana; Integrated approach to deep fat frying: engineering, nutrition, health and consumer aspects. J. Food Eng., **56**, 143-152 (2003).

[5] M. H. Gamble, P. Rice, J. D. Selman; Relationship between oil uptake and moisture loss during frying of potato slices from c.v. Record U.K. tubers. Int. J. Food Sci. Technol., **22**, 233–241 (1987).

[6] R. G. Moreira, X. Sun, Y. Chen; Factors affecting oil uptake in tortilla chips in deep fat frying. J. Food Eng., **31**: 485–498 (1997).

[7] M. K. Krokida, V. Oreopoulou, Z. B. Maroulis, D. Marinos-Kouris; Effect of pre-drying on quality of French fries. J. Food Eng., **49**, 347–354 (2001).

[8] R. C. Baker, D. Scott-Kline; Development of a high protein coating batter using egg albumen. Poultry Sci., **67**, 1742–1745 (1986).

[9] S. Mohamed, N. A. Hamid, M. A. Hamid; Food components affecting the oil absorption and crispness of fried batter. J. Sci. Food Agric., **78**, 39–45 (1998).

[10] S. Mohamed, S. M. M. Lajis, N. A. Hamid; Effects of protein from different sources on the characteristics of sponge cakes, rice cakes (Apam), doughnuts and frying batters. J. Sci. Food Agric., **68**, 271–277 (1995).

[11] F. Shih, K. Daigle; Oil uptake properties of fried batters from rice flour. J. Agric. Food Chem., **47**, 1611–1615 (1999).

[12] B. Altunakar, S. Sahin, G. Sumnu; Functionality of batters containing different starch types for deep-fat frying of chicken nuggets. Eur. Food Res. Technol., **218**, 318–322 (2004).

[13] C. R. Southern, X. D. Chen, M. M. Farid, B. Howard, L. Eyres; Determining internal oil uptake and water content of fried thin potato crisps. Trans. Inst. Chem. Eng., Part C, **78**, 119–125 (2000).

[14] AOAC. Official Methods of Analysis. The Association of Official Analytical Chemists. 16th ed. Washington D.C (1995).

[15] J. M. Aguilera, D. W. Stanley; Microstructural principles of food processing and engineering. 2nd ed. Publishers, Aspen, Maryland, 1999.

[16] P. Bouchon, P. Hollins, M. Pearson, D. L. Pyle, M. J. Tobin; Oil distribution in fried potatoes monitored by infrared microspectroscopy. J. Food Sci., **66**, 918–923 (2001).

[17] M. H. Gamble, P. Rice; The effect of slice thickness on potato crisp yield and composition. J. Food Eng., **8**, 31–46 (1988).

[18] D. Lund; Influence of time, temperature, moisture, ingredients, and processing conditions on starch gelatinization. Crit. Rev. Food Sci. Nutri., **20**, 249–273 (1984).

[19] N. Mittleman, S. Mizrahi, Z. Berk; "Heat and mass transfer in frying," Engineering and food, Vol. 1: Engineering sciences in the food industry, ed. by B.M. McKenna, pp. 109-116, Publisher, Elsevier Applied Science, NY (1984).

[20] P. Rice, M. H. Gamble; Technical note: Modeling moisture loss during potato slice frying. Int. J. Food Sci. Tech., **24**, 183–187 (1989).

[21] J. F. Velez-Ruiz, F. T. Vergara-Balderas, M. E. Sosa-Morales, J. Xique-Hernandez; Effect of temperature on the physical properties of chicken strips during deep-fat frying. Int. J. Food Prop., **5**, 127–144 (2002).

[22] S. N. Marousis, G. D. Saravacos; Density and porosity in drying starch materials. J. Food Sci., **55**, 1367–1370, 1372 (1990).

[23] H. Watanabe, M. Fukuoka, A. Tomiya, T. Mihori; A new non-Fickian diffusion model for water migration in starchy food during cooking. J. Food Eng., **49**, 1–6 (2001)

「日本食品工学会誌」, Vol. 6, No. 2, pp. 143 - 149, Jun. 2005

◇◇◇ 和文要約 ◇◇◇

小麦粉・水 混合モデル食品のフライ調理における脱水率および油吸収度に及ぼす初期水分含量の影響

Pariya THANATUKSORN[1], Chidphong PRADISTSUWANA[2], Pantipa JANTAWAT[2], 鈴木　徹[1]

[1]東京海洋大学海洋科学部　[2]チュラロンコン大学

フライ調理は世界的にも主要な調理手法であり，各国で古くから利用されてきた．近年では，調理冷凍食品産業，ファーストフード産業などにおいても大量に生産される機会が多くなっている．健康問題，また資源・環境問題からフライ調理品に油脂吸収残存を少なくする努力が払われている．しかし，フライ調理過程は熱移動，水分の蒸発と拡散，デンプン糊化，タンパク質変性が相互に関連しながら進む非常に複雑な過程であり，そのメカニズムに関する科学的理解は十分とはいえない．欧米ではポテトフライを食すことが多く，ポテトを対象としたフライ調理研究が多い．また，衣を付けたフライ食品も比較的多く，バッターに関する研究も見られる．しかし，それらは断片的であり，フライ調理過程を体系的に捉えようとした試みはなかった．水分含量に着目した場合，フライ調理の対象となる食品は初期水分含量（IMC）によってその呼び名が異なり，それぞれ個別の研究対象とされてきた．例えば，小麦粉に対して水分が少ない場合はドウ，水分が多いとバッターとされる．本研究では，そういった（小麦粉ー水）の混合物を1つの系ととらえ，水分含量を「ドウ」のレベルである40%から「バッター」の領域80%まで大幅に変化させてフライ調理過程の相違を調べ，そのメカニズム解明の手がかりを探った．

小麦薄力粉に対して，40，60，70，80%の水分含量になるように調整した試料をフラットな円盤状（厚さ約2 mm）に成型，あるいは型に流し込み，その試料を150°Cのパーム油中で7分までフライ調理を行い，油から取り出したのち，数分間冷却を行った．フライ中また，冷却中2分ごとに試料を取り出し，残存水分含量，油吸収率の時間経過を調べた．また同時に，各時間経過後における，それぞれの試料の微細構造を走査型電子顕微鏡にて観察した．

その結果，初期水分含量IMC40，60，70%の試料では5～7分間のフライ過程後期では，十分な脱水が進行し残存水分含量に有意な差がみられなかったが，IMC80%試料では他の試料に比較してやや多くの水分が残存する傾向がみられた．一方，油吸収量の時間的推移はIMC40，60，70%の試料ではフライ加熱中に油が多く吸収され冷却期間では大きく増加しなかった．これに対して，IMC80%試料では油吸収のパターンに他試料と明らかな相違がみられた．すなわち，IMC80%試料はフライ加熱時には油の吸収は低く抑えられているものの，冷却時に急激に油が吸収されるといった現象が明確に確認された．

また，それら速度過程を検討するために水分の一次元移動拡散律速を想定して水分減少と油吸収量をフライ時間tの平方根に対してプロットしたところ，水分減少はいずれの初期水分でも直線関係が得られた．しかし，油の吸収量は初期水分が80%の場合には$t^{1/2}$に比例するものの，IMC70%以下では直線関係は得られなかった．さらに，初期水分含量で残存水分を割り基準化した水分減少率で脱水過程を比較検討したところ，初期水分含量が70%以下の試料はほぼ同一の曲線に従うものの，IMC80%の試料のみ逸脱したカーブを示した．SEMの観察結果とあわせて検討したところ，IMC70%以下では澱粉の糊化による水分の吸収と水分の蒸発脱水が同時に進行するが，IMC80%試料では澱粉の糊化が著しく多量の水分を吸収し蒸発が少ないことが示唆された．油の吸収速度と水分蒸発速度との関係Fig. 7は，上記推論を裏づける結果を示した．すなわち，初期水分含量が70%以下の場合にはいずれの初期水分含量でも同一の曲線に乗り，水分の蒸発速度が大きいフライ初期では油の吸収速度は小さく，水分が少なく水分の蒸発速度が低くなるに従って急激に油の吸収速度が上昇する傾向がみられた．これは油の吸収は初期水分含量に関係なく水分の蒸発速度だけによって制御されていることを意味し，水分が蒸発し続けている間は蒸気圧によって油が侵入できないといったメカニズムが働いていると考えられる．

一方，初期水分80%の試料では水分は澱粉の糊化に使われ蒸発する水分は少なく，油の浸入は容易と考えられるが，十分糊化した澱粉糊にはポアが少なく油が侵入するスペースがなく澱粉糊がフィルムとなって逆に油の進入を抑えているメカニズムが作用していると考えられる．

以上，小麦粉ー水の混合物のフライ過程では混合比が澱粉の糊化に影響を与え，それが水分の蒸発速度に影響をおよぼし結果として油の吸収速度に影響をおよぼしていることが推察された．また，そのメカニズムの変化が初期水分70%から80%の間で起こることも明らかとなった．しかし，本研究ではフライ過程でのデンプンの糊化についての直接情報がなく糊化との関係については多くの推察が含まれる．今後，本研究の結論を確実なものにするためにはフライ時のデンプンの糊化進行についての実証研究が必要となると考えられる．

（受付2005年1月17日，受理2005年3月14日）

† Fax: 03-5463-0585, E-mail: toru@s.kaiyodai.ac.jp