Journal of the Science of Food and Agriculture *J Sci Food Agric* **85**:2574–2580 (2005)
DOI: 10.1002/jsfa.2300

Effect of surface roughness on post-frying oil absorption in wheat flour and water food model

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Abstract: The effects of surface roughness and post-fried cooling time on oil absorption were investigated for a food model comprised of various wheat flour and water mixtures. The models were prepared by varying the initial moisture contents as 400, 600 and 800 g kg^{-1}. The samples were then fried at 150 °C in palm olein oil for 5 min and then left to cool down for 0, 1, 3 or 6 min. Fractal analysis was used to evaluate the resulting surface roughness of samples fried for 5 min. The results revealed that the average fractal dimension increased as the sample's initial moisture was increased. The adhered oil on the surface decreased with cooling time; however, the absorbed oil increased. The surface roughness that is generated during frying causes the quantity of adhered oil to increase during the initial cooling stage. As cooling progresses, the surface oil is absorbed by the sample in proportion to the fractal dimension and the initial moisture content.

Keywords: moisture content; cooling time; surface roughness; fractal dimension; oil absorption

INTRODUCTION

Deep-fat frying is a complex process where heat and mass transfer occur simultaneously.[1] Heat transfer changes the physical and chemical properties of food, and mass transfer causes the water in the food to vaporize and diffuse into the surrounding oil as the oil penetrates into the food.[2] Although the absorbed oil adds flavor to fried foods,[3] a high oil content causes human health and lifestyle problems. Recent research on oil content reduction in fried foods revealed that oil uptake is affected by many factors including initial moisture content, frying time and temperature, quality and composition of the frying oil, interfacial tension, surface area and porosity.[1,4] Most of these studies, however, report the results for a specific type of product and cannot be generalized. Therefore, the overall factors and mechanisms of oil uptake during frying are still unclear.

It is obvious that the surface and pore structure of a product is the dominating factor in oil absorption. Gamble and Rice[5] preliminarily reported that potato chip oil uptake is directly proportional to its surface area. Moreira *et al*[6] observed that more frying oil adhered to the puffing area than to the inner portion of fried tortilla chips. More recently, Rubnov and Saguy[7] have reported that the surface roughness fractal dimensions in restructured potato products correlate linearly with the final oil uptake amount.

The results of these studies are significant; however, the overall mechanism is not apparent because only the final oil uptake amount was considered. Fried food oil uptake is considered to be the combination of frying and post-frying effects; however the previous studies did not distinguish between the two. To understand better the fried food oil uptake process, the different mechanisms in the frying and post-frying phases need to be detailed. Gamble *et al*[8] have already proposed the importance of the post-frying process on oil uptake in potato chips. When the chips are removed from the fryer, steam condenses in the pores as a result of the drop temperature. This, in turn, produces a vacuum within the potato chip pores. During this period, any oil that has not been drained from the product is sucked into the pores by the vacuum. The smaller the amount of adhered oil, the lower is the final oil content. Although this discovery was only observed in potato chips, it may be applicable for all fried products. In general, the frying process changes the

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Contract/grant sponsor: Thailand–Japan Technology Transfer Project (TJTTP–OECF)
Contract/grant sponsor: Office of Affairs, Chulalongkorn University
(*Received 12 August 2004; revised version received 28 January 2005; accepted 4 April 2005*)

surface structure, and the surface structure regulates the amount of oil that will adhere to the surface during the post-frying phase. It should be stressed, however, that this generalized assumption for fried products has not been proved experimentally.

Furthermore, only a few articles concerning the oil uptake in batter used for products such as fried fish and fried chicken is available, while there are a vast number of reports on potato and corn-based product research, as described above. Mukprasirt *et al*[9] reported that batters that contain pregelatinized or modified corn flour instead of ordinary wheat flour form crispy coatings with a lower final oil content than that of the ordinary wheat flour batter. Mohamed *et al*[10] reported that increasing the initial water content in rice flour batter leads to greater porosity and more oil absorption in the fried coating because of its lower viscosity and higher evaporation rate during frying. However, it should be noted that the change in oil uptake in this research was small because there were only slight variations in the initial moisture content. Shih and Daigle[11] reported that substituting rice flour for the main batter component increases oil resistance. Altunakar *et al*[12] indicated that using difference starch types in the nuggets coating resulting in differences in crispness and oil content. These studies have investigated the effects of batter composition on oil uptake. However, there has been no systematic attempt to discover the oil uptake mechanism with regard to batter products.

This study attempts to discuss the oil uptake of fried products more generally, without product distinctions. The main component of the general model sample is wheat flour, and the initial moisture content was varied as 400, 600 and 800 g kg^{-1}. Using these model samples, the relationship between the changing surface roughness due to the initial moisture content and the resulting oil uptake during the frying and post-frying periods are studied. It should be noted that this study was conducted in a similar way to the research of Rubnov and Saguy,[7] who studied the correlation of surface roughness and final oil uptake in restructured potatoes. This study, though, investigates the relationships in a more generalized fashion.

MATERIALS AND METHODS

Sample preparation and frying

The model samples were prepared using wheat flour consisted of 81.9 g kg^{-1} gluten (United Flour Mill Co. Ltd, Thailand) at initial moisture levels of 400, 600 and 800 g kg^{-1} (by wet basis). These levels were achieved by mixing the flour with distilled water at room temperature (25 °C) for 15 min. Because the 400 g kg^{-1} sample has the consistency of dough, it was reformed between two rolls (150-mm deluxe, Atlas, Padua, Italy) until a final thickness of 0.8 mm was achieved. The sample was later cut by a circular stainless steel mold into a 5-cm diameter circular disk, weighing 3.00 ± 0.05 g.

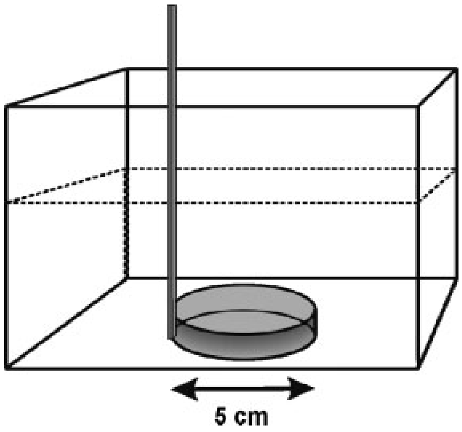

Figure 1. Diagram showing the Teflon coated circular mold using for frying the 600 g kg^{-1} and 800 g kg^{-1} sample.

The two batter-like samples, consisting of 600 and 800 g kg^{-1} moisture levels, were weighed into 5-cm diameter Teflon-coated circular molds, weighing 4.50 ± 0.05 and 9.00 ± 0.05 g, respectively, as shown in Fig 1. The weights of these three types of samples were strategically chosen so that they would contain equal quantities of wheat flour.

All three types of samples were then deep-fat fried in an oil bath (Thermo-mate BF600, Yamato, Japan) containing 3 l of palm olein oil (Thai Olene Co. Ltd, Bangkok, Thailand) at 150 °C for 1, 3 and 5 min. 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 3 h. Therefore, the oil used in this study was discarded after 3 h of frying. After frying, the samples were left to cool at room temperature for 0, 1, 3 or 6 min. Once the cooling was complete, the oil adhered to the surface was measured by dipping the samples into a beaker containing 100 ml of petroleum ether for 2 s. The petroleum ether was then evaporated and the remaining oil was weighed. Southern *et al*[13] previously used this method for the same purpose. The oil absorbed by the sample was determined by Soxhlet extraction according to the method of the AOAC.[14] These values were based on the dried and defatted sample weight.

Statistical analysis

All of the trials incorporated the Asymmetric Factorial Experiment (3 × 3 × 4) with two replicates. The SPSS software program was used to perform the ANOVA and Duncan's new multiple range tests[15] on the resulting data.

Evaluation of surface roughness

Fractal analysis has recently been applied in food studies to describe the roughness of instant coffee particles,[16] to evaluate the surface porosity of modified starch granules[17] and to interpret the crunchiness of snacks from stress–strain relationships.[18,19] The fractal dimension describes the degree of irregularity 1–2 for a line and 2–3 for a surface. The higher the fractal dimension, the higher the level of irregularity.

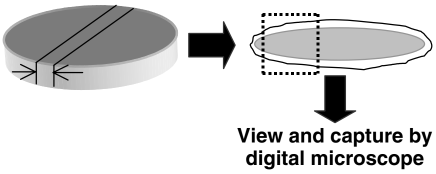

Figure 2. Diagram showing the cross-section of fried sample for fractal analysis.

This study employs a fractal analysis technique called the box-counting method[20] to determine the fractal dimension for the surface contours. This value is interpreted as the surface roughness index for the actual surface. The box-counting method involves covering the surface with a grid. The relationship between the number of grids covering a surface contour N and the size of the grids P, correspond to a box size expressed by eqn (1).

$$N\alpha\ P^{-D} \tag{1}$$

where N = the number of grids covering the contour, P = the size of grids, D = the fractal dimension.

The fractal dimension of the surface contours can be obtained from the slope of the log–log plot of N *versus* P. Fractal analysis software was used to perform this analysis on 20 2-mm surface contour images that were arbitrarily chosen from each moisture level sample.

In order to observe better the sample surface, the wheat flour was mixed with a commercial fabric dye (Dylon multi-purpose dye, London, UK) at 0.1 g kg^{-1} by weight of flour before it was mixed with distilled water. The resulting dough and batter samples were deep-fat fried at 150 °C for 5 min. The fried samples were then immediately dipped in petroleum ether and remained there for 24 h. Next, the samples were placed in melted paraffin at 80 °C for 5 min. The fixed samples were then microtomed (Erma-300, Erma, Tokyo, Japan) into thin sections approximately 0.5 mm thick. Five samples were produced for each moisture level, and four sections from each sample were observed, as shown in Fig 2. A digital microscope (QX3plus, Intel, CA, USA) at 60× magnification was used to view and capture the surface edge images, which were then converted into the surface edge contours shown in Fig 3.

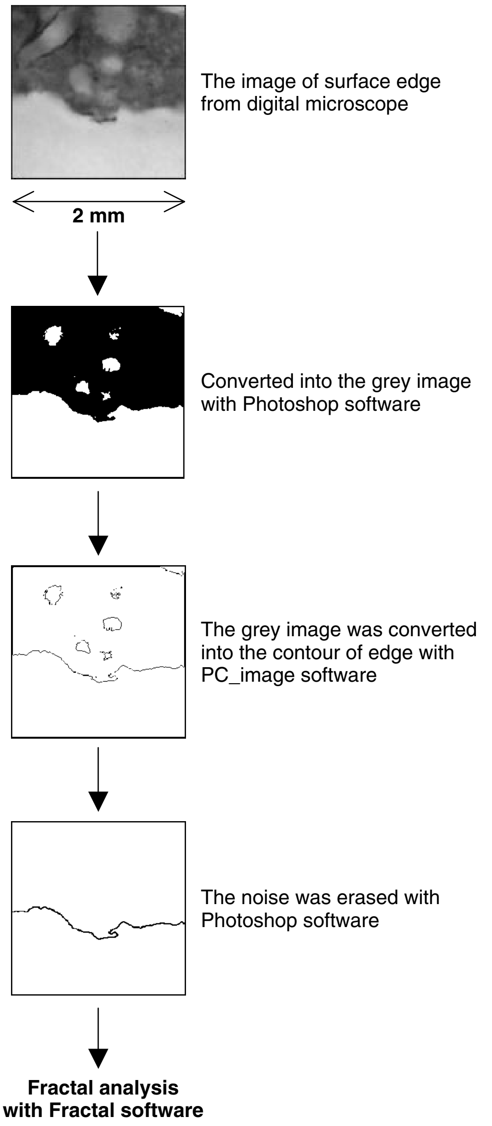

Figure 3. Diagram showing the procedure of converting the surface edge image into the surface contour for fractal analysis.

RESULTS AND DISCUSSION

Surface roughness

The fractal analysis technique was used to determine the surface roughness of the samples. Figure 4 displays some typical examples of cross-sectional images for the fried samples. The log–log plot of N and P showed a linear trend. The exponent in the equation, ie the slope of the log–log plot, is the fractal dimension of the surface contour. From these figures, the slope of 800 g kg^{-1} initial moisture sample was higher than the others. It is obvious that the initial moisture level affects the sample's appearance and the surface roughness. The greater the initial moisture content, the rougher the surface. Figure 5 shows the distribution of fractal dimensions. As the moisture content of the sample increased, the fractal dimension shifted to a higher value. The representative fractal dimension for each sample was determined by averaging the results from 20 images. The initial moisture content significantly influences the average fractal dimension of fried sample surface ($P \leq 0.05$). The surface roughness is linearly proportional to the initial moisture value, as shown in Fig 6 ($R^2 = 0.98$). The higher the initial moisture, the greater the surface roughness. Bouchon *et al*[21] stated that higher steam pressures induce higher initial moisture levels, which cause surface disruptions in the food samples. The results from this study quantitatively support this assertion.

Adhered oil content on surface during frying and cooling

The change in the quantity of adhered oil during frying and cooling is shown in Fig 7. During frying, the

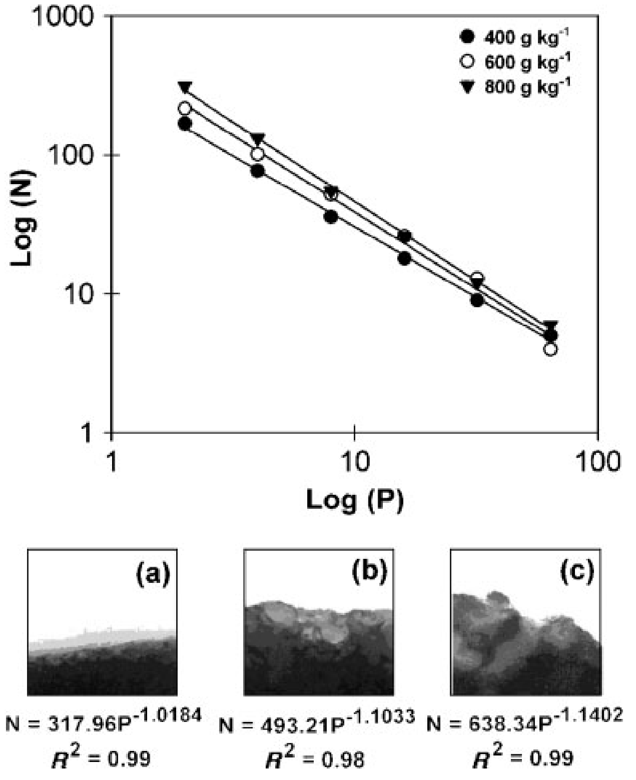

Figure 4. The example of log–log plot for determining fractal dimension in (a) 400, (b) 600 and (c) 800 g kg^{-1} initial moisture sample fried at 150 °C for 5 min.

quantity of surface oil for the 400 and 600 g kg^{-1} initial moisture samples remained constant. The quantity of oil on the 800 g kg^{-1} initial moisture sample, though, decreased with frying time due to sample shrinkage for frying times over 1 min. This surface oil quantity decreased because the shrinkage reduced the total surface area. The quantity of surface oil on the 400 and 600 g kg^{-1} samples remained unchanged because the sample diameters remained stable. The diameter changed during frying for 800 g kg^{-1} sample, but the effects of these changes are on a much smaller scale than the developing in the surface roughness. During the post-frying phase, called the cooling period, the surface oil levels dramatically dropped during the first minute, and then continued to slightly decline thereafter. This may be due to the fact that when the samples were removed from the frying oil, a certain level of water vapor remained in the sample. Then, as the sample temperature drops, the water vapor inside the sample's pores condenses, resulting in a vacuum within the pore. This vacuum sucks in the adhered oil. This result supports previous findings[22,23] stating that adhered oil is responsible for oil absorption during post-frying.

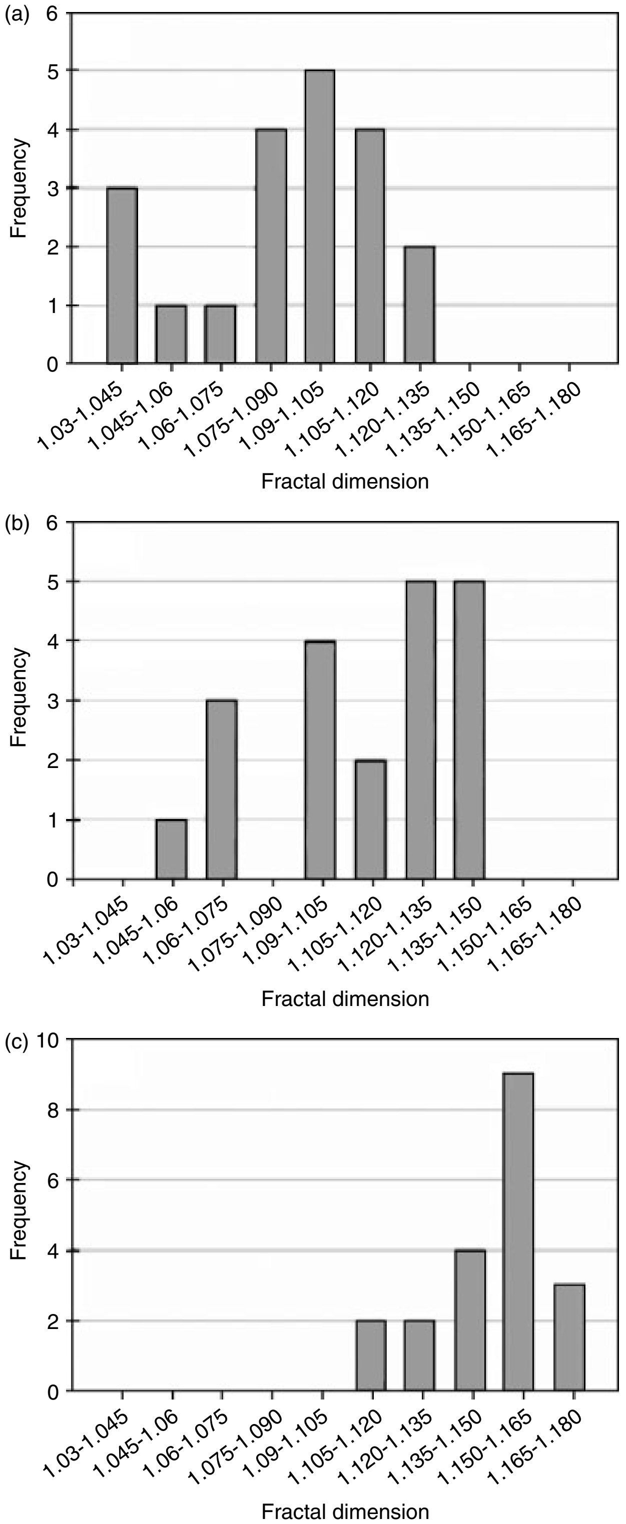

Figure 5. Distribution of fractal dimension of (a) 400, (b) 600 and (c) 800 g kg^{-1} initial moisture content sample fried at 150 °C for 5 min.

The initial value of the adhered oil profile in Fig 7 shows the amount of adhered oil that could not be drained from the fried sample surface when it was removed from the fryer. The adhered oil content at the initial cooling (0 min of cooling of the samples fried at 5 min) increased as initial moisture content increased. The relationship between fractal dimension and the initial adhered oil quantity (0 min) is depicted in Fig 8. The fractal dimension for this cooling stage was $R^2 = 0.85$. Samples with higher moisture content provide more places where water evaporation can occur, resulting in higher surface roughness. Because higher levels of water evaporation during frying increases surface roughness therefore, more oil adheres to the increased surface area.

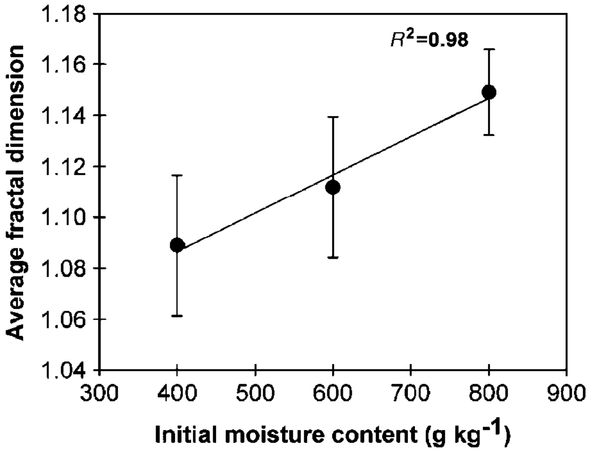

Figure 6. The relationship between initial moisture content of the samples fried at 150 °C for 5 min and the average fractal dimension. Each average fractal dimension was calculated from twenty data. The error bars: the standard deviation ±0.027, ±0.027, and ±0.016 for 400, 600, and 800g kg^{-1} sample respectively.

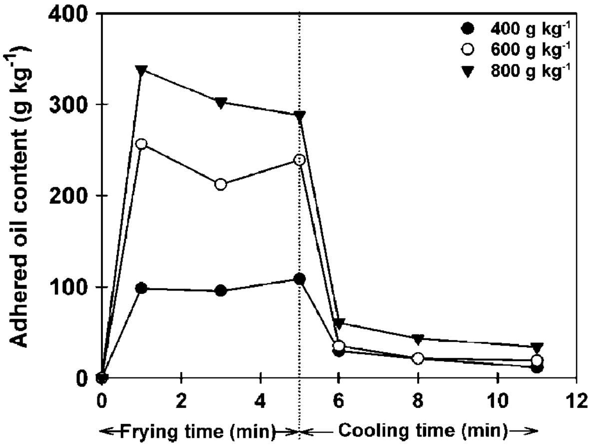

Figure 7. Effect of initial moisture content on adhered oil contents during frying and cooling of wheat flour model.

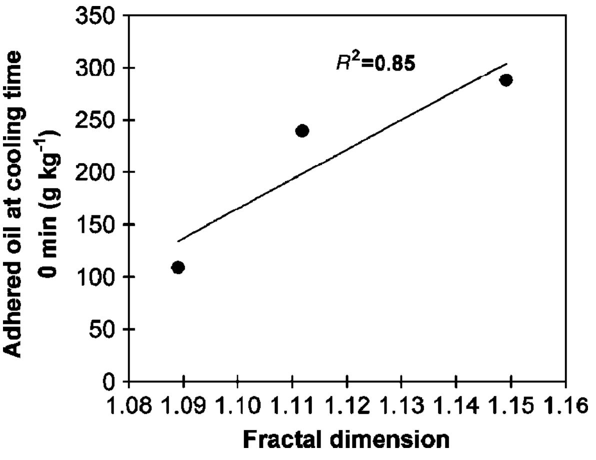

Figure 8. The relationship between the adhered oil at the initial cooling time (0 min of cooling) of the sample fried at 150 °C for 5 min and average fractal dimension.

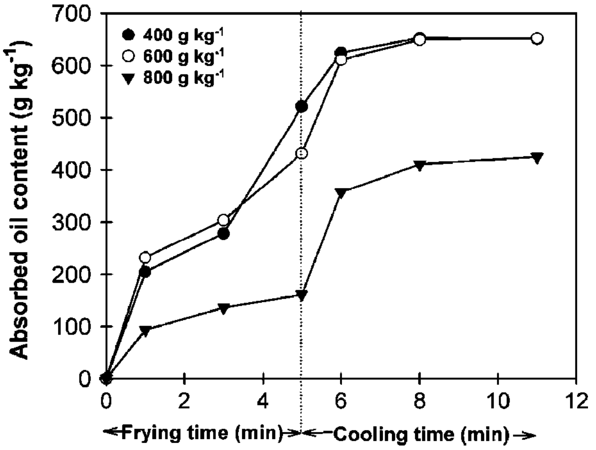

Figure 9. Effect of initial moisture content on absorbed oil content during frying and cooling of wheat flour model.

Internal oil content during frying and cooling

Figure 9 depicts the changes in the level of absorbed oil during the frying and cooling processes. It is assumed that oil absorption occurs during both processes. After five minutes of frying, the absorbed oil contents for the 400, 600 and 800 g kg^{-1} initial moisture samples were 521, 431 and 160 g kg^{-1} (dry basis), respectively. The smaller the initial moisture content in the sample, the higher is the quantity of absorbed oil. These results can be attributed to water evaporation during frying. In the deep-fat frying process, the surface temperature rapidly rises when the sample is submerged in the oil, and the water on the surface starts evaporating. During this period, the oil does not penetrate into the sample. As the sample continues to fry, the quantity of water on its surface declines, the internal water heats up and the frying oil begins to penetrate the sample. The water inside the 400 and 600 g kg^{-1} samples dramatically diminishes during the early frying stage. Meanwhile, the water evaporation on the surface of the 800 g kg^{-1} sample continues to be high for a given frying time and temperature. Therefore, the oil content of the 800 g kg^{-1} sample is lower than for the 400 and 600 g kg^{-1} samples. In addition, the water to starch ratio affects starch gelatinization, which also influences oil penetration during frying. For the 800 g kg^{-1} samples, the water amount was sufficient enough to form a strong gel structure that retards water loss, resulting in lower oil absorption.

Once frying was complete, the samples were immediately removed from the oil. During this initial post-frying period, the quantity of absorbed oil increased sharply, and then the oil absorption rate declined as the cooling continued. Hence, the quantity of absorbed oil was the opposite of that for the adhered oil (Figs 7 and 9). The oil absorption rate for of all of the samples increased significantly during the initial period and then stabilized after 3 min had passed. Aguilera and Gloria-Hernandez[23] reported somewhat similar findings. When frozen pre-fried potatoes were fried at 180 °C for 150 s and then allowed to cool at room temperature for 15 s, the temperature within sample rapidly decreased from 180 °C to under 100 °C. They proposed that during this period a high suction pressure was generated

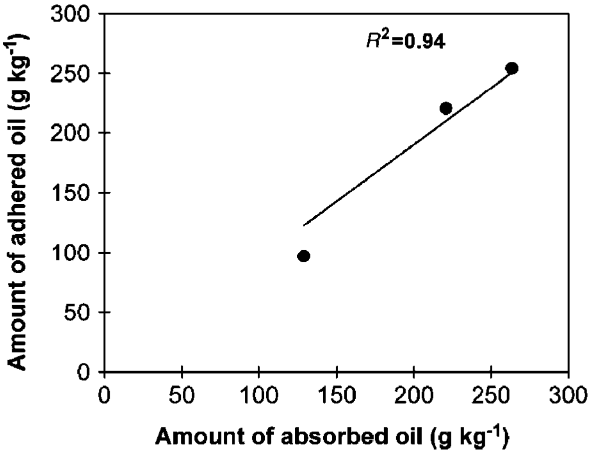

Figure 10. The relationship between the amount of absorbed oil and adhered oil during the cooling period after 0 and 6 min of cooling.

within the food matrix. After 15 s, the temperature decreased to below 100 °C and the pressure dropped. As a result, the rate of oil absorption became constant as the cooling time extended. Kawas and Moreira[17] concluded that the majority of the oil absorption in tortilla chips occurred during the cooling period, rather than frying. The results of this study do not fully agree with this assertion. The majority of oil absorption for the 400 and 600 g kg^{-1} moisture samples occurs during the frying stage. The oil absorption rate during the initial cooling period for the 800 g kg^{-1} moisture model was considerably higher than that for the 400 and 600 g kg^{-1} samples, as shown in Fig 9. These results suggest that water content directly impacts the change in surface irregularity, thereby influencing oil absorption during the post-frying period.

As previously mentioned, increases in the oil content during the post-frying process are a result of an induced vacuum that sucks the surface oil into the sample's pores. The relationship between the amount of absorbed oil and adhered oil during the cooling period was determined by calculating the changes in absorbed oil and adhered oil after 0 and 6 min of cooling, as shown in Fig 10. The difference in the quantity of adhered oil from 0 to 6 min is the amount of adhered oil that was pulled into the sample, becoming absorbed oil. It was observed that the amount of adhered oil is linearly proportional to the amount of absorbed oil ($R^2 = 0.94$). These results confirm that the surface oil was pulled into the sample. These experiments have shown that surface irregularities caused by initial moisture affect the oil absorption mechanism during cooling.

CONCLUSIONS

This study showed that oil absorption occurs during both frying and post-frying. Initial moisture content was found to be the major factor governing oil uptake. The moisture influenced the surface alterations during frying. The larger the amount of initial moisture, the higher is the surface roughness and the higher the oil absorption during cooling. The results of these experiments have supported previous assertions that pressure induced in the sample's pores affect oil absorption, however, surface roughness also plays a significant role during post-frying. The oil absorption in fried food can be impeded by rapidly reducing the quantity of adhered oil immediately after removing the product from the fryer, or by somehow decreasing the surface roughness generated during frying.

ACKNOWLEDGEMENTS

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 research.

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