Food Chemistry 115 (2009) 999–1005

Contents lists available at ScienceDirect

Food Chemistry

journal homepage: www.elsevier.com/locate/foodchem

Analysis of wheat gluten and starch matrices during deep-fat frying

A.M. Gazmuri, P. Bouchon *

Department of Chemical and Bioprocess Engineering, Pontificia Universidad Católica de Chile, P.O. Box 306, 6904411 Santiago, Chile

ARTICLE INFO

Article history:
Received 20 August 2008
Received in revised form 13 November 2008
Accepted 13 January 2009

Keywords:
Deep-fat frying
Oil uptake
Gluten
Starch

ABSTRACT

An important quality parameter of fried food is the amount of oil uptake, which is incompatible with recent consumer trends towards healthier food. The oil penetration mechanism is not fully understood but study of formulated products is a good way to elucidate the role of the food matrix in oil absorption.

In this context, the oil absorption capacity of a restructured matrix, made with native wheat starch and vital wheat gluten, was examined. Four different product formulations were analysed, using 2 levels of gluten content (8% and 12% d.b.) and 2 levels of water content (38% and 44% w.b.). Dough was sheeted into 2 thicknesses (1 and 2 mm) and cut into discs that were either directly fried or fried after predrying with dry air (2 min at 150 °C).

Results showed that gluten had a predominant role in the structure, making the dough more elastic and less permeable to oil absorption. High gluten content resulted in lower oil uptake in products with low moisture content. Overall, predried discs absorbed, on average, half of the oil of undried samples. Interestingly, even though predried products with high gluten content had a higher moisture content before frying, they absorbed a low amount of oil, suggesting that oil uptake is not clearly related to the amount of moisture lost but rather to product microstructure.

1. Introduction

Food processing is facing new challenges, which include providing, in addition to microbiologically safe and high quality foods, products that fulfil the new demands of well-informed consumers. People ask that products contribute to their wellness and health, but they also require specific textures, flavours, colours, and certainly, a consistent food. That is, consumers expect minimal variations in food products from batch to batch. This product-driven process engineering era, as coined by Aguilera (2006), requires the building of controlled structures and therefore, understanding of the functionality of the structural elements prior to or during processing. In the light of this approach, product formulation appears as a good alternative for developing new products with controlled attributes. Accordingly, formulated products are gaining importance in the snack industry as a good alternative to the use of raw materials, because of the advantages of reproducibility, uniformity and lack of defects (Gebhardt, 1996) in contrast, for instance, to potato, whose heterogeneity can cause major variations in final products (Baumann & Escher, 1995).

Deep-fat frying is one of the oldest and most common unit operations used in the preparation of processed foods, and is especially suited to develop snacks with unique flavours and textures. It can be defined as a process for cooking foods, by immersing them in edible oil, at a temperature above the boiling point of water, usually between 160 and 190 °C, under atmospheric conditions (Farkas, 1994). The process involves simultaneous heat and mass transfer, which cause significant microstructural changes to both the surface and the body of the product. Heat transferred from the oil into the food causes protein denaturation, starch gelatinisation, water vapourisation, crust formation and colour development, which are typical phenomena of the combined effects of multiple-order chemical reactions (Singh, 1995). Mass transfer is characterised by the loss of water from the food as water vapour and the movement of oil into the food (Dobraszczyk, Ainsworth, Ibanoglu, & Bouchon, 2006). It is not clearly understood how oil uptake takes place, but there is some experimental evidence showing that water loss and oil absorption are asynchronous phenomena. It has been proposed that, during frying, the vigorous escape of water vapour would generate a barrier to prevent oil migration into the porous structure and, as a consequence, oil absorption would be limited during most of the immersion period. As a result, oil uptake would be essentially a surface-related phenomenon resulting from the competition between drainage and suction into the porous crust once the product is removed from the oil and begins to cool (Moreira, Sun, & Chen, 1997; Ufheil & Escher, 1996).

Crust permeability is therefore a critical parameter and has been considered as the main determining factor in oil uptake (Bouchon, Hollins, Pearson, Pyle, & Tobin, 2001; Pinthus, Weinberg, & Saguy, 1995). In fact, most of the pre-frying treatments oriented to reduce oil absorption are focused on altering crust permeability.

* Corresponding author. Tel.: +56 2 3547962; fax: +56 2 3545803.
E-mail address: pbouchon@ing.puc.cl (P. Bouchon).

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doi:10.1016/j.foodchem.2009.01.020

Among them, we can find pre-frying treatments, such as hot-air drying and baking (Gamble & Rice 1987; Lamberg, Hallstrom, & Olsson, 1990) which, rather than merely reducing initial water content, as is usually believed, induce surface structural changes that limit the absorption (Moreno & Bouchon, 2008). The use of hydrocolloids with thermal gelling or thickening properties such as methylcellulose, hydroxypropyl methylcellulose, long fibre cellulose, corn zein and alginates, to reduce oil absorption, is also well documented (Albert & Mittal, 2002; García, Ferrero, Bertola, Martino, & Zaritzky, 2002). Their ability to reduce oil absorption is mainly based on their film-forming properties and crust-porosity reduction. The hydrocolloid mixture can be added to the product in several ways: (1) directly in the formula, such as in doughnuts and formulated products, (2) included in a batter or breading or (3) sprayed onto the product as a solution (Pinthus, Weinberg, & Saguy, 1993). In formulated products, the permeability of the outer layer of the product also depends on the thickness of the sheeted dough, which determines the structural resistance to water vapour escape. A stronger and more elastic network can result in a less permeable outer layer that may act as an effective barrier against oil absorption (Bouchon & Pyle, 2004).

Many formulated products are based on wheat flour (among other components). Wheat popularity is largely determined by the ability of wheat flour to be processed into different foods, which is mainly given by the unique properties of wheat-flour gluten proteins (Anjum, Khan, & Din, 2007). Products based on wheat flour dough are widely used in frying operations to produce products such as doughnuts, battered food and fritters, but they may also be sheeted and cut into small pieces to be fried. Wheat gluten's unique viscoelastic properties improve dough strength, mixing tolerance, and handling properties. Its film-forming ability provides gas retention and controlled expansion for improved volume, uniformity and texture, whereas its thermosetting properties contribute to structural rigidity and its water absorption capacity improves baked product yield, softness and shelf-life (Day, Augustin, Batey, & Wrigley, 2006). In relation to deep-fat frying, Fiszman, Salvador, and Sanz (2005), when frying battered squid rings, showed that the addition of gluten reduced oil absorption but, at the same time, it significantly increased moisture retention, resulting in a lower density and, consequently, a more porous and crunchier final batter texture. On the other hand, Rovedo, Singh, and Normen (1998) studied the effect of adding gluten to a potato starch-based dough and concluded that a higher gluten content caused an increase in oil uptake and a considerable expansion of the product. Gluten has also been used as an edible coating in fried products, due to its film-forming capacity and its barrier properties towards oil and water vapour (Albert and Mittal, 2002).

Another important constituent of wheat flour dough is water. To obtain suitable dough, the appropriate amount of water must be present. There is always competition among flour components for water, which makes water content a critical factor. Also, water is one of the most important constituents that determine the texture of fried foods. In the process of water vapourisation, the molecular volume of water increases rapidly as a result of the phase change from liquid to gas. When water vapour does not have a clear passage to the food/oil interface, this increase may lead to volume expansion of the fried food. In addition, volume expansion of water contributes to the porous structure of the crust and the rate of dehydration influences pore size distribution. Volume expansion also depends on the relative ease of migration of water through the surface matrix, which depends on the strength of the structure (Chen, Chang, & Hsieh, 2001).

From the previous discussion, it can be seen that the role of gluten and water in a dough matrix (to be fried) is of scientific interest. In fact, formulated sheeted products based on wheat flour could make it possible to investigate the effects of different product formulations on oil absorption, contributing to the understanding of the mechanisms that may be involved. Despite the interest, there is little research on this topic. Most of the articles that study the role of wheat flour constituents during frying are based on battered or breaded products, and the focus is centred on the structures formed by gluten and the impact of the batter on the quality parameters of the product (Fiszman et al., 2005; Hernando et al., 2007; Mohamed, Hamid, & Hamid, 1998). Accordingly, the main objective of this paper is to study the effects of gluten content, water content and dough thickness on oil uptake, and associated quality attributes, such as colour development and product expansion, during deep-fat frying. Experimental procedures are based on a formulated product made of a reconstituted blend of gluten and wheat starch instead of wheat flour, in order to accurately control ingredient proportions. The effect of a drying pretreatment on the different quality attributes of the fried product is also analysed.

2. Materials and methods

2.1. Materials

The product to be fried was a restructured matrix made of native wheat starch and vital wheat gluten (Asitec S.A., Chile), plus distilled water. The oil used was high oleic sunflower oil (Camilo Ferrón, Chile), which was kept constant for all experiments.

2.2. Sample preparation protocol

Samples were prepared ensuring two different water levels in the dough, 38 and 44% (w.b.). The amount of water added depended on the initial water content of the ingredients and was adjusted to ensure that all different products contained the specified amount. To do so, the exact water content of ingredients was determined experimentally by drying in a forced air oven at 105 °C for 24 h (to constant mass). For each of the two moisture content doughs, two dry mixture blends were prepared, containing either 8 or 12% gluten (% d.b.). In this way, only the dry ingredient proportion was modified.

The ingredients were mixed and sieved with a 40 mesh sieve (W.S.Tyler, USA). To form the dough, distilled water was added to the specific dry mixture blend, until it reached either 38 or 44% water content (w.b.). Half of the water was added at 15 °C while mixing for 1 min, using a 5K5SS mixer (KitchenAid, USA). After mixing for 2 min, the rest of the water was added. This water fraction was heated at 100 °C, and was also poured while mixing for 1 min. After mixing, the dough was sheeted using a LSB516 dough sheeter (Doyon, Canada) until reaching a final thickness of either 1 or 2 mm. The sheeted dough was then cut manually into 3.8 cm diameter discs.

Discs were either directly fried or fried after a predrying step. Drying was carried out under controlled conditions, using a Self-Cooking Center Model SCC661 (Rational, Germany), with dry air at 150 °C for 2 min. The drying time was kept constant in all formulations to study the effect of gluten moisture retention capacity during drying, and subsequently, during deep-fat frying.

2.3. Frying

Frying was carried out in an electrically heated fryer (model DF535T, Somela, Chile), which was thermostatically controlled to maintain the set frying temperature ±2 °C using an electrical control system ((PID + Fuzzy Logic, Veto, Chile). The fryer was filled with 4 l of oil, which were preheated for 2 h prior to frying and discarded after frying for 3 h. The frying temperature was set for all the experiments at 170 °C.

Six discs, previously weighed in an analytical balance (model GR-200, And, Japan; $d = 0.1$ mg), were placed inside the frying basket and covered with a grid to prevent them from floating. Frying was carried out by immersing the basket in the oil for 1, 2 and 3 min for the 2 mm thickness discs and for 30 s and 1 min for the 1 mm thickness discs, ensuring reaching the bubble-end point. After each frying time, the samples were removed from the fryer and were held in a stainless steel grid for 10 min.

No de-oiling system was used in any experiment in order to determine the total oil content absorbed by the samples. All experiments were run in triplicate; that is, three batches were made for each product formulation.

2.4. Analytical methods

2.4.1. Oil content and moisture loss

After frying, fried products were ground and weighed. The oil content was determined by solvent extraction using the Soxhlet technique (AOAC, 1995). Each extracted group was then dried in a forced air oven at 105 °C for 24 h (to constant mass), cooled in a desiccator and then weighed to obtain the dry solids content. The moisture content was obtained from the difference between the original weight and the dry solids plus the oil content.

Moisture loss was reported on a dry basis and was calculated from the difference between the original moisture content and the moisture content after frying.

2.4.2. Colour analysis

2.4.2.1. Image acquisition and capture. Colour measurement was done using the technique explained by Papadakis, Malek, Kamdem, and Yam (2000). The technique involves setting up a lightning system, using a high resolution camera to capture images and Photoshop software to obtain colour parameters.

The image acquisition system consisted of a colour digital camera, model PowerShot A70 (Canon, USA), connected to a computer USB interface IFC-300PCU (Canon, USA), mounted on a stand inside a large box impervious to light with internal black surfaces. The lighting system consisted of four CIE source D65 lamps (60 cm length and 18 W; Model TLD/965, Philips, Singapore) placed above the sample at a 45° angle to maximize diffuse reflection responsible for colour. The angle between the camera lens axis and the sample was around 90°, to reduce gloss. A Kodak gray card with 18% reflectance was used as a white reference to standardise the illumination level before each session (Briones & Aguilera, 2005). The iris was operated in manual mode, with a lens aperture of $f = 8$ and a speed 1/3 (1/6) (no zoom, no flash) to achieve high uniformity and repeatability.

Samples were placed in the field of view of the camera and an image of 1600 × 1200 pixels was acquired and stored in JPEG format of high resolution and fine quality, in RGB colour coordinates.

2.4.2.2. Colour measurement. L, a, b coordinates were obtained using Adobe Photoshop 6.0 software (Adobe Systems Inc., USA.), which were thereafter normalised to L^*, a^*, b^* coordinates, according to Eqs. (1)–(3) (Yam & Papadakis, 2004).

$$L^* = \frac{L}{255} \cdot 100 \quad (1)$$

$$a^* = a \cdot \frac{240}{255} - 120 \quad (2)$$

$$b^* = b \cdot \frac{240}{255} - 120 \quad (3)$$

The colour difference between raw (L_0^*, $a_0^* b_0^*$) and fried discs (L^*, a^*, b^*) was determined by taking the Euclidean distance between them, according to Eq. (4) (Mariscal & Bouchon, 2008):

$$\Delta E^* = \left[(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2 \right]^{1/2} \quad (4)$$

2.5. Expansion analysis

The expansion developed in each product was determined using a Vernier Caliper. Expansion was defined as the maximum height developed during frying (H). In addition, maximum and minimum diameters were measured (D1 and D2). Generally the samples preserved their round shape, so the difference between these two diameters was not significant.

2.6. Statistical analysis

Statistical analysis was done using Statgraphics for Windows software, version 5.1 (Manugistic Inc., Rockville, MD, USA). Results were compared using analysis of variance, Duncan's multiple range contrast and Kruskal-Wallis contrast with 95% confidence level.

3. Results and discussion

3.1. Moisture loss

Fig. 1 shows moisture losses for increasing times when frying thin and thick discs, which were either directly fried (left hand side) or dried prior to frying (right hand side).

With regard to undried samples, it can be observed that the initial water loss rate was higher for the 1 mm thickness product compared to the 2 mm one. This may occur because, in a thinner product, water is closer to the surface, but also because of the stronger structure that is developed in the thicker product, which inhibits water escape. Gluten showed a statistically significant effect ($p < 0.05$) in moisture-loss rate when frying dough with 38% water content; the dough with the higher gluten content presented a lower rate, the difference being clearer in the thicker product. This aspect is certainly linked to the capacity of the gluten network to retain water (Fiszman et al., 2005). On the other hand, products with different gluten contents did not present any statistical difference when frying dough with 44% water content, suggesting that water escape cannot be effectively precluded by the gluten network in a high moisture content dough.

In relation to predied samples, it must be remembered that all samples were predried under the same conditions (2 min with dry air at 150 °C), in order to study the water retention capacity of the different formulations. Table 1 shows the average moisture content (% d.b.) after drying and therefore before frying. As in frying, gluten played an important role in retaining water in the structure during drying. For the two levels of moisture content and for the two different thicknesses, products with lower gluten content lost more water during the drying step than did those with higher gluten content. It can be observed (right hand side of Fig. 1) that thin products with higher gluten content presented higher moisture loss during frying, according to their initial moisture level. In thick discs, no significant differences were found when comparing predried discs made from dough with an initial moisture content of 38%. However, when comparing predried thick discs made from dough with an initial moisture content of 44%, results changed. Even though samples with higher gluten content had higher initial moisture level prior to frying, they retained water for a longer time. This may be due to the development of a stronger structure and associated surface changes occurring during drying,

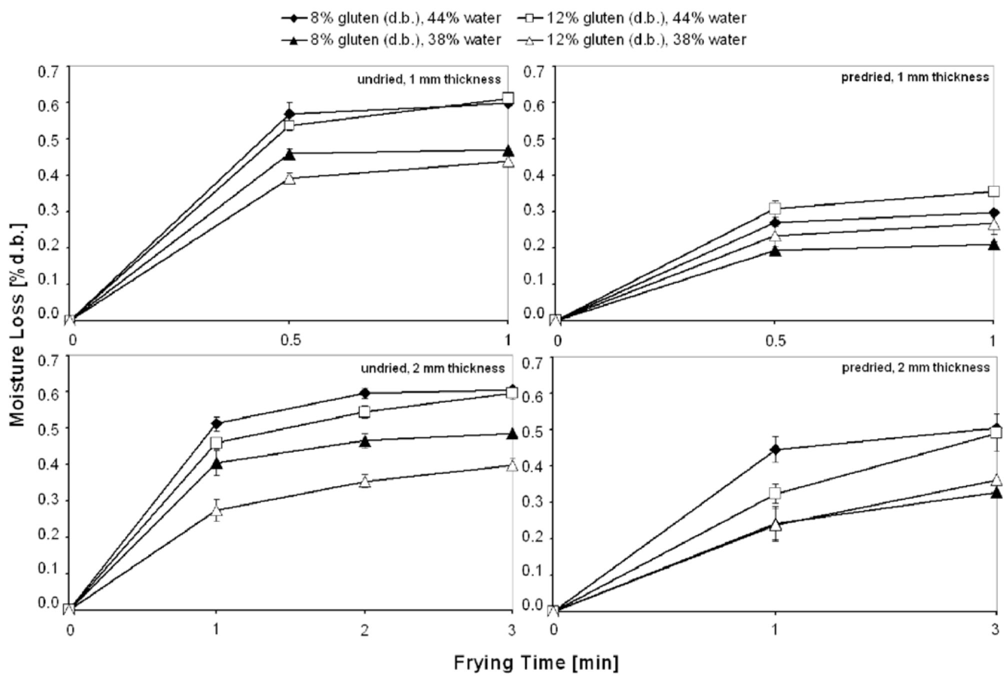

Fig. 1. Moisture loss (% d.b.) for increasing times when frying thin and thick discs made with different formulations, which were either directly fried (left hand side) or dried prior to frying (right hand side). Points are means ± standard error.

Table 1
Moisture content (% d.b) of products with 38 and 44% water content, with two levels of gluten content and two different thicknesses, after drying with dry air at 150 °C for 2 min. Data are means ± standard error.

	Moisture content before frying (d.b.)			
	8% Gluten (d.b.)		12% Gluten (d.b.)	
	38% Water	44% Water	38% Water	44% Water
1 mm thickness	0.23 ± 0.01	0.34 ± 0.03	0.32 ± 0.04	0.39 ± 0.01
2 mm thickness	0.35 ± 0.03	0.53 ± 0.01	0.40 ± 0.04	0.56 ± 0.01

which result in a less permeable surface that decreases water loss rate at early stages.

3.2. Oil uptake

Fig. 2 shows oil uptake (% d.b.) of products with 38 and 44% water content, with two levels of gluten content and two different thicknesses, for increasing frying times. When analysing dough with 38% water content (top of Fig. 2), it can be observed that products with lower gluten content absorbed more oil. For instance, in thin products at the bubble-end point, the product with 8% gluten (d.b.) absorbed 32% more oil than did the product with 12% gluten (d.b.). In products of 2 mm thickness, the effect of gluten content was even more significant. At bubble-end point, a 45% difference in oil uptake was found when comparing both formulations. Overall, the statistical analysis showed that gluten content had a significant effect on oil uptake ($p < 0.05$).

On the other hand, in formulations with 44% water content (bottom of Fig. 2), products with different gluten contents did not show any significant difference in oil uptake, when sheeted into either thin or thick discs. This may be directly related to what was found in terms of moisture loss, where no differences were determined between the 2 mixtures when working with a 44% water content dough. Higher water content means a higher amount of bubbles escaping from the product, which may rupture the inner structure, impairing the effect of gluten on oil uptake reduction.

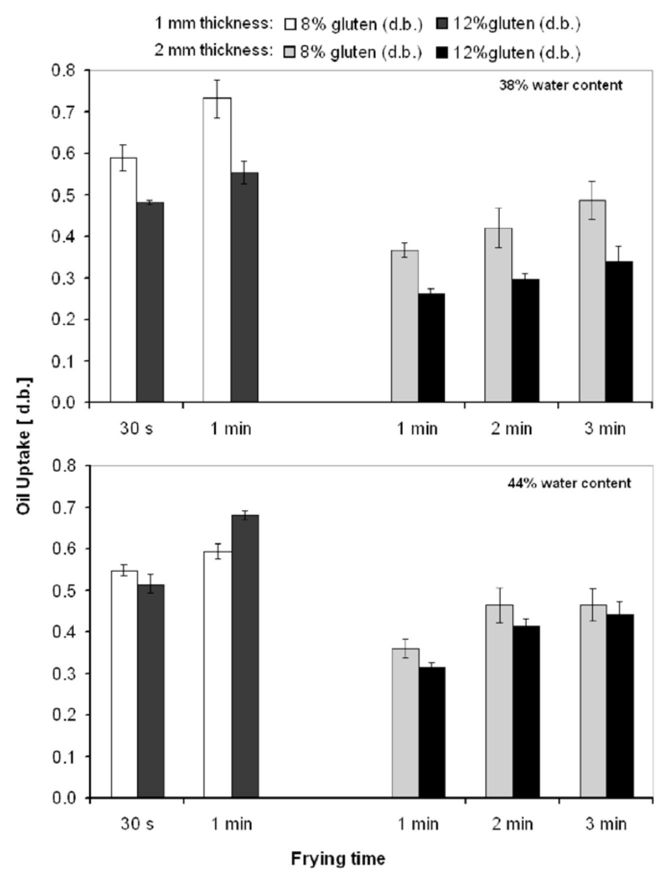

Fig. 2. Oil uptakes (% d.b.) of products with 38% or 44% water content, with two levels of gluten content and two different thicknesses, for increasing frying times. Points are means ± standard error.

When comparing oil uptakes of thin and thick products, it can be clearly observed that thinner products absorbed proportionally more oil, the difference being significant for each of the four formulations. As stated previously, products with a greater surface area per unit volume are expected to absorb more oil, since oil uptake is essentially a surface-related phenomenon. Also, the structure of a thinner product is weaker and may provide little resistance, and therefore more permeability to oil penetration, as found in related studies (Bouchon & Pyle, 2004). At bubble-end point, the difference in oil uptake between thin and thick products was on average 48%. The difference was more pronounced in products with higher gluten content, probably because they build a stronger structure when sheeted into a thick product.

Fig. 3 shows the effect of gluten content on oil uptake when frying predried discs made from dough with initial water contents of 38% and 44% (top and bottom of Fig. 3, respectively). Gluten had a significant effect, in all products, for both initial water content levels, whether they were sheeted into thin or thick discs. Interestingly, even though samples with higher gluten content had higher initial moisture levels after drying (Table 1), they absorbed a significantly lower amount of oil. The amount of oil uptake has generally been related to the amount of moisture lost. In fact, several studies claim that higher initial moisture content results in an increased oil uptake, since water evaporation defines the volume of the oil reservoir, through the empty spaces, as it leaves the structure (Gamble, Rice, & Selman, 1987). However, in these experiments, moisture content was not the most relevant parameter determining oil absorption, but rather the gluten content. In fact, products with higher gluten content had a higher initial moisture level, and therefore lost a higher amount of water until reaching bubble-end point; however, oil absorption was significantly lower. At bubble-end point, thin products with 8% gluten (d.b.) absorbed 25% more oil than did those with 12% gluten (d.b.), the difference being similar for both levels of initial water content. On the other hand, in thick products, the effect was more pronounced in products with 38% water content than in those with 44% water content. In contrast to what happened with undried discs, in predried discs made from dough, with an initial water content of 44%, the increase in gluten content had a significant effect on oil uptake reduction. This result reinforces the hypothesis that an increase in gluten content would reduce oil absorption when frying dough with low moisture content.

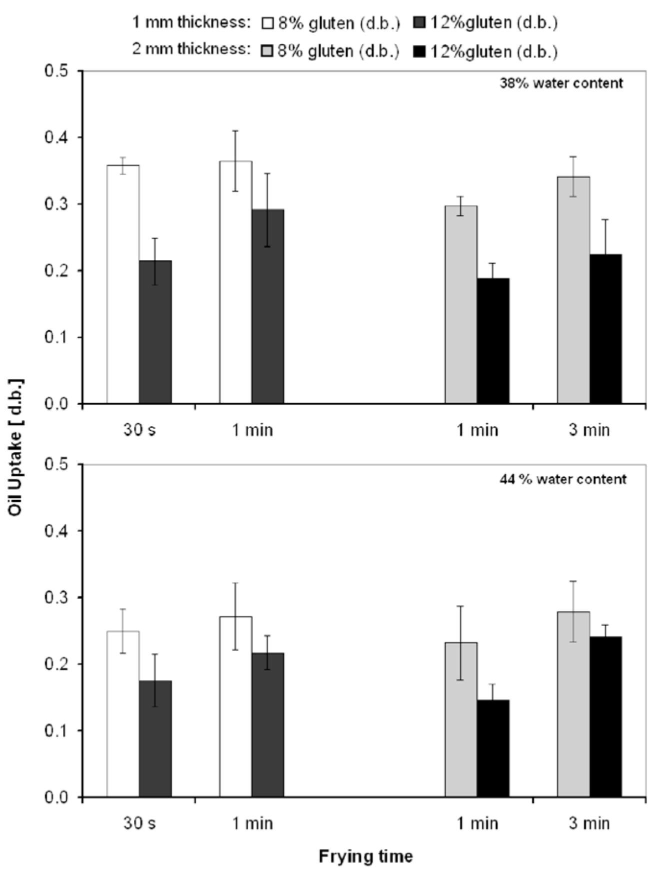

Fig. 3. Oil uptakes (% d.b.) of predried products made from dough with an initial water content of 38% or 44%, with two levels of gluten content and two different thicknesses, for increasing frying times. Points are means ± standard error.

3.3. Colour development

The colour of fried food is one of the most significant quality factors for its acceptance. Non-enzymatic browning during frying is a result of reaction between reducing sugars and aminoacids at high temperatures. The concentrations of proteins, aminoacids and reducing sugars, the process temperature and the frying time affect colour and flavour development in the fried product (Maroulis, Krokida, Oreopoulou, & Marinos-Kouris, 2001). Colour change (ΔE^*) was determined according to Eq. (4) and results are summarised in Table 2. Values of ΔE^* were between 2 and 4 times higher in the 2 mm thickness products than in thin samples, at bubble-end point. The decrease in moisture content associated with crust formation and increasing temperature in the crust layer may accelerate non-enzymatic browning. Although thin and thick products at bubble-end point had the same moisture contents, colour change was greater in thick products, since the dehydrated outer surface was exposed to high temperatures for a much longer time.

ΔE^* was significantly different when comparing products with different gluten or water contents. Both higher gluten content and higher water content resulted in lighter products. Probably both effects are related, given the previous discussion about the role of gluten in retaining water in the structure. If a higher water content implies a lower ΔE^* value, then it is expected that a higher gluten content will have the same effect. Predried discs were significantly darker than undried ones ($p < 0.05$). Analysis of the whole set of data showed that neither gluten nor water content had a statistically significant effect in the colour of predried samples.

Table 2
Colour change (ΔE^*) after frying (up to bubble-end point) thin and thick discs made with different formulations, which were either directly fried or dried prior to frying. Data are means ± standard error.

	Colour difference between raw and fried discs (ΔE^*)							
	Undried				Predried			
	44% Water dough		38% Water dough		44% Water dough		38% Water dough	
	8% Gluten	12% Gluten	8% Gluten	12% Gluten	8% Gluten	12% Gluten	8% Gluten	12% Gluten
1 mm thickness	8.09 ± 0.62	3.94 ± 0.30	11.02 ± 0.62	4.58 ± 0.78	19.65 ± 0.99	11.55 ± 0.54	12.46 ± 0.36	9.74 ± 0.71
2 mm thickness	19.93 ± 2.72	15.91 ± 2.85	35.28 ± 2.32	23.74 ± 1.98	46.11 ± 0.62	31.32 ± 1.60	25.96 ± 1.63	32.06 ± 1.60

3.4. Expansion development

Fig. 4 shows expansion development of the different products at bubble-end point. In all cases, the maximum height (*H*) was found in the product containing the highest amounts of gluten and water. On the other hand, the less expanded ones were those prepared with the lowest amounts of gluten and water. Certainly, high gluten content dough helps to develop an elastic structure that traps water vapour, producing an expanded product. In thin products, the effect of gluten was more significant than the effect of water, suggesting that dough with low gluten content is not elastic enough to withstand vigorous water escape. On the other hand, in thick undried discs, expansion was similar when comparing dough with 44% water and 8% gluten (d.b.) and dough with 38% water and 12% gluten (d.b). That is, dough with low gluten content was able to retain water vapour in a better way when sheeted into a thick product. But, at the same time, dough with low water content was not able to expand the strong structure formed in a thick disc made from dough with high gluten content.

Predried sample expansion was significantly lower (40% on average) and mean diameters were significantly smaller (on average, 3.5 cm against 3.7 cm), than in the undried counterparts. Drying not only induced case-hardening but it also decreased initial water content, precluding vapour escape during frying. The most important difference was found for the product containing 8% gluten (d.b.) and 44% water; predried samples where more than 60% less expanded than undried ones. Overall, when analysing the whole set of data, gluten content was the most significant factor determining product expansion in predried discs.

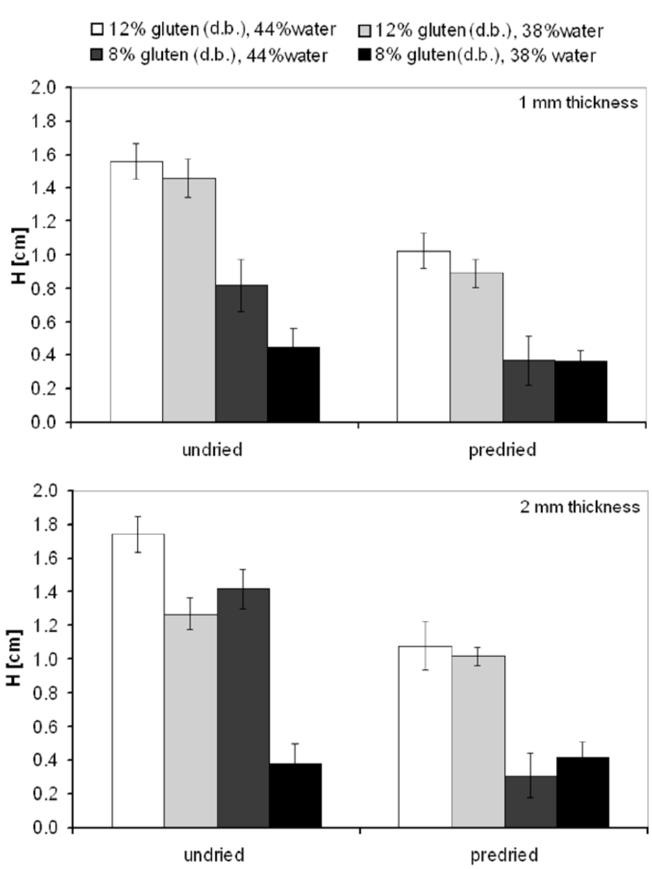

Fig. 4. Maximum height (cm) developed after frying (up to bubble-end point) thin and thick discs made with different formulations, which were either directly fried (left hand side) or dried prior to frying (right hand side). Points are means ± standard error.

Interestingly, if results from Fig. 4 are compared to those obtained in terms of oil uptake (Figs. 2 and 3), it may be observed that oil absorption is not related to product expansion, confirming that oil absorption seems to be a surface phenomenon.

4. Conclusion

Results obtained in the present study show that gluten film-forming capacity seems to be the most relevant factor influencing oil uptake when deep-fat frying a food matrix made of wheat starch, gluten and water. In fact, dough with higher gluten content presented a significant reduction in oil uptake in almost every case under study (dried or undried) with the exception of products with high moisture content. This was probably because high water content led to explosive vapourisation, creating tissue disruption, and therefore, increasing surface permeability to oil absorption. Interestingly, even though predried discs with 8% gluten (d.b.) lost more water during the drying step compared to products with 12% gluten (d.b.), they absorbed a significantly higher amount of oil, showing that oil uptake is not clearly related to the amount of moisture lost but rather to product microstructure and external layer permeability. Overall, predried discs absorbed, on average, half as much oil when compared to undried samples, reflecting the effects of shrinkage and case-hardening, on oil surface permeability. Results did not show any relationship between product expansion and oil absorption, supporting the hypothesis that oil absorption is a surface phenomenon. This study shows how food building blocks (gluten, starch and water in this case) may be combined in order to obtain desired quality parameters.

Acknowledgements

The authors appreciate financial support from FONDECYT project number 1070764.

References

Aguilera, J. M. (2006). Food products engineering: Building the right structures. *Journal of the Science of Food and Agriculture, 86*(8), 1147–1155.

Albert, S., & Mittal, G. S. (2002). Comparative evaluation of edible coatings to reduce fat uptake in a deep-fried cereal product. *Food Research International, 35*(5), 445–458.

AOAC, Assoc. Official Analytical Chemists (1995). *Official methods of analysis* (16th ed.). Washington, DC: Association of Official Analytical Chemists.

Anjum, F. M., Khan, M. R., & Din, A. (2007). Wheat gluten: High molecular weight glutenin subunits-structure, genetics and relation to dough elasticity. *Journal of Food Science, 72*(3), R56–61.

Baumann, B., & Escher, E. (1995). Mass and heat transfer during deep fat frying of potato slices – I. Rate of drying and oil uptake. *Lebensmittel-Wissenschaft und-Technologie, 28*(4), 395–403.

Bouchon, P., Hollins, P., Pearson, M., Pyle, D. L., & Tobin, M. J. (2001). Oil distribution in fried potatoes monitored by infrared microspectroscopy. *Journal of Food Science, 66*(7), 918–923.

Bouchon, P., & Pyle, D. L. (2004). Studying oil absorption in restructured potato chips. *Journal of Food Science, 69*(3), FEP115–FEP122.

Briones, V., & Aguilera, J. M. (2005). Image analysis of changes in surface color of chocolate. *Food Research International, 38*(1), 87–94.

Chen, C. S., Chang, C. Y., & Hsieh, C. J. (2001). Improving the texture and color of fried products. In J. B. Rossell (Ed.), *Frying: Improving quality*. USA: Woodhead Publishing Ltd and CRC Press LLC.

Day, L., Augustin, M. A., Batey, I. L., & Wrigley, C. W. (2006). Wheat-gluten uses and industry needs. *Trends in Food Science and Technology, 17*(2), 82–90.

Dobraszczyk, B. J., Ainsworth, P., Ibanoglu, S., & Bouchon, P. (2006). Baking, extrusion and frying. In J. G. Brennan (Ed.), *Food processing handbook*. USA: John Wiley & Sons.

Farkas, B. E. (1994). *Modeling immersion frying as a moving boundary problem*. Ph.D thesis, University of California, Davis, USA.

Fiszman, S. M., Salvador, A., & Sanz, T. (2005). Effect of the addition of different ingredients on the characteristics of a batter coating for fried seafood prepared without a pre-frying step. *Food Hydrocolloids, 19*(4), 703–708.

Gamble, M. H., & Rice, P. (1987). Effect of pre-fry drying on oil uptake and distribution in potato crisp manufacture. *International Journal of Food Science and Technology, 22*(5), 535–548.

Gamble, M. H., Rice, P., & Selman, J. D. (1987). Relationship between oil uptake and moisture loss during frying of potato slices from c.v. Record U.K. tubers. *International Journal of Food Science and Technology, 22*(3), 233–241.

García, M. A., Ferrero, C., Bertola, N., Martino, M., & Zaritzky, N. (2002). Edible coatings from cellulose derivatives to reduce oil uptake in fried products. *Innovative Food Science and Emerging Technologies, 3*(4), 391–397.

Gebhardt, B. (1996). Oils and fats in snack foods. In Y. I. Hui (Ed.). *Bailey's industrial oil and fat products* (Vol. 3, pp. 409–428). New York, Chichester: Wiley.

Hernando, I., Llorca, E., Perez-Munuera, I., Quiles, A., Larrea, V., & Lluch, M. A. (2007). The structure of starch granules in fried battered products. *Food Hydrocolloids, 21*(8), 1407–1412.

Lamberg, I., Hallstrom, B., & Olsson, H. (1990). Fat uptake in a potato drying/frying process. *Lebensmittel-Wissenschaft und-Technologie, 23*, 295–300.

Mariscal, M., & Bouchon, P. (2008). Comparison between atmospheric and vacuum frying of apple slices. *Food Chemistry, 107*(4), 1561–1569.

Maroulis, Z. B., Krokida, M. K., Oreopoulou, V., & Marinos-Kouris, D. (2001). Color changes during deep fat frying. *Journal of Food Engineering, 48*(3), 219–225.

Mohamed, S., Hamid, N. A., & Hamid, M. A. (1998). Food components affecting the oil absorption and crispness of fried batter. *Journal of the Science of Food and Agriculture, 78*(1), 39–45.

Moreira, R. G., Sun, X., & Chen, Y. (1997). Factors affecting oil uptake in tortilla chips in deep-fat frying. *Journal of Food Engineering, 31*(4), 485–498.

Moreno, M. C., & Bouchon, P. (2008). A different perspective to study the effect of freeze, air, and osmotic drying on oil absorption during potato frying. *Journal of Food Science, 73*(3), E122–128.

Papadakis, S. E., Malek, S. A., Kamdem, R. E., & Yam, K. L. (2000). A versatile and inexpensive technique for measuring color of foods. *Food Technology, 54*(12), 48–51.

Pinthus, E. J., Weinberg, P., & Saguy, I. S. (1993). Criterion for oil uptake during deep-fat frying. *Journal of Food Science, 58*(1), 204–205. 222.

Pinthus, E. J., Weinberg, P., & Saguy, S. (1995). Deep-fat fried potato product oil uptake as affected by crust physical properties. *Journal of Food Science, 60*(4), 770–772.

Rovedo, C. O., Singh, R. P., & Normen, E. (1998). Mechanical properties of an immersion fried potato starch-gluten gel during postfrying period. *Journal of Texture Studies, 29*(6), 681–697.

Singh, R. P. (1995). Heat and mass transfer in foods during deep-fat frying. *Food Technology, 49*(4), 134–137.

Ufheil, G., & Escher, F. (1996). Dynamics of oil uptake during deep-fat frying of potato slices. *Lebensmittel-Wissenschaft und-Technologie, 52*(3), 640–644.

Yam, K. L., & Papadakis, S. E. (2004). A simple digital imaging method for measuring and analyzing color of food surfaces. *Journal of Food Engineering, 61*(1), 137–142.