Available online at www.sciencedirect.com
ScienceDirect
Food Chemistry 107 (2008) 1561–1569
Food Chemistry
www.elsevier.com/locate/foodchem

Comparison between atmospheric and vacuum frying of apple slices

M. Mariscal, P. Bouchon *

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

Received 10 July 2007; received in revised form 24 July 2007; accepted 11 September 2007

Abstract

Vacuum deep-fat frying is a new technology that can be used to improve quality attributes of fried food because of the low temperatures employed and minimal exposure to oxygen. In this paper atmospheric and vacuum frying of apple slices were compared, in terms of oil uptake, moisture loss and color development. In addition, some apple slices were pre-dried (up to 64% w.b.) before vacuum frying to determine the overall effect. To carry out appropriate comparisons between both technologies equivalent thermal driving forces were used in both processes ($\Delta T = 40$, 50, 60 °C), keeping a constant difference between the oil temperature and the boiling point of water at the working pressure. Vacuum frying was shown to be a promising technique that can be used to reduce oil content in fried apple slices while preserving the color of the product. Particularly, drying prior to vacuum frying was shown to give the best results. For instance, when using a driving force of $\Delta T = 60$ °C, pre-dried vacuum fried slices absorbed less than 50% of the oil absorbed by atmospheric fried ones. Interestingly, a strong relationship between water loss and oil content was observed in both technologies, allowing the extension of observations that have been made for atmospheric frying.

Keywords: Vacuum frying; Oil uptake; Apple; Deep-fat frying

1. Introduction

Deep-fat frying is one of the oldest and most common unit operations used in the preparation of foods, since it results in products with a unique flavor-texture combination (Varela, 1988). However, numerous studies have revealed that excess consumption of fat, a main component in deep-fat fried food, is a key dietary contributor to coronary heart disease and perhaps cancer of the breast, colon, and prostate (Browner, Westenhouse, & Tice, 1991). Despite recent consumer trends towards healthier food, consumption of oils and fats is still high. For instance, in the United States consumers eat four or more snacks a day and consume more than 6.5 billion pounds of snack food annually. As such, salty snacks account for slightly over half of total snack sales and are consequently a large part of the American diet (Mintel, 2006).

Key growth categories are those that offer a wide range of product alternatives, adhering to convenience, sensory and health trends. In terms of health, interest in salty snack products that are organic or all natural, low-calorie, low-fat, low-carbohydrate, low-sodium or offer some health-promoting benefit, are in greater demand by consumers. Although consumers are interested in healthier snack products, they are not willing to sacrifice flavor. Intense and full-flavor snacks remain an important trend in the salty snack market.

Deep-fat frying is defined as a process where a food is cooked by immersing it in an edible oil or fat heated above the boiling point of water. The process is traditionally carried out under atmospheric conditions and the frying temperature is usually near to 180 °C (Dobraszczyk, Ainsworth, Ibanoglu, & Bouchon, 2006). It is a complex unit operation involving high temperatures, significant microstructural changes both to the surface and the body of the chip, and simultaneous heat and mass transfer, resulting in flows in opposite directions of water vapor (bubbles)

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

0308-8146/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.foodchem.2007.09.031

and oil at the surface of the piece (Bouchon, Hollins, Person, Pyle, & Tobin, 2001). In fact, numerous studies have shown that oil uptake during deep-fat frying is confined to the surface region of the fried product and restricted to a depth of a few cells (Farkas, Singh, & McCarthy, 1992; Keller, Escher, & Solms, 1986; Saguy, Gremaud, Gloria, & Turesky, 1997) and that oil uptake is essentially a surface-related phenomenon resulting from the competition between drainage and suction into the porous crust once the fried potato is removed from the oil and begins to cool (Bouchon, Aguilera, & Pyle, 2003; Gamble, Rice, & Selman, 1987; Moreira, Sun, & Chen, 1997; Ufheil & Escher, 1996).

Based on the previous mechanisms many oil reduction techniques have been proposed and developed. Post-frying treatments such as hot air drying (Nonaka, Sayre, & Weaver, 1977) and super-heated steam drying (Kochhar, 1999) are two processes which have shown to reduce significantly oil absorption after frying. Also different pre-frying treatments have shown to be effective in reducing the absorption. Lowering the moisture content of the food prior to frying using microwave, hot-air treatment and baking has resulted in a significant reduction in oil content in different products (Gamble et al., 1987; Krokida, Oreopolou, Maroulis, & Marinos-Kouris, 2001; Lisinska & Leszczynski, 1991; Moyano, Rioseco, & Gonzalez, 2002). In addition, much attention has been given to the use of hydrocolloids such as methylcellulose, hydroxypropyl methylcellulose, long fibre cellulose and corn zein, to reduce surface permeability and inhibit oil uptake (Bouchon & Pyle, 2004). In terms of quality improvement, besides oil uptake reduction, the blanching step prior to frying has shown to improve color and texture (Fan, Zhang, & Mujumdar, 2005; Lisinska & Leszczynski, 1991; Pedreschi & Moyano, 2005; Shyu & Hwang, 2001).

Vacuum frying is a new technology that might be an option for the production of novel snacks, such as fruits and vegetables, with lower oil content and desired quality attributes. It is defined as the frying process carried out under pressures well below atmospheric levels, therefore lowering the boiling point of water, making possible to reduce substantially the frying temperature (Garayo & Moreira, 2002). In the literature, only few works are found in relation to this topic since research in this field is initiating. At present, vacuum frying has shown to have some advantages that include: (1) reduction of the oil content in the fried product, (2) preservation of natural color and flavors and (3) reduction of adverse effects on oil quality (Garayo & Moreira, 2002; Shyu, Hau, & Hwang, 2005). Granda, Moreira, and Tichy (2004) have concluded that vacuum frying can also diminish acrylamide (an animal carcinogen compound) content in potato crisps. Overall, benefits are mainly derived from the low temperatures employed and minimal exposure to oxygen. In terms of the raw materials under study, most researches have been oriented towards potatoes and only few works based in other foods are found (Shyu & Hwang, 2001; Shyu et al., 2005).

In relation to the effect of frying conditions, Garayo and Moreira (2002) observed that oil absorption in potato crisps was related to the moisture lost during the process and that color was not significantly affected by the oil temperature (118, 132 and 144 °C) and vacuum pressure used (16.661, 9.888 and 3.115 kPa). On the other hand, Shyu and Hwang (2001), when studying the effect of processing conditions on the quality of vacuum fried apple chips using a single vacuum pressure condition (3.115 kPa), and three different oil temperatures (90, 100, 110 °C), concluded that oil content increased for increasing frying times and temperatures.

In order to compare atmospheric and vacuum frying it would be interesting to study the effect of equivalent driving forces in both processes on the main quality attributes of the product (e.g. oil content and color development). This could be accomplished by maintaining the same thermal driving force, that is, by keeping a constant difference between the oil temperature and the boiling point of water at the working pressure (atmospheric or vacuum pressure). In addition, vacuum deep-fat frying could be combined with other pre-treatments such as drying, to determine if there could be any synergism. In accordance, the main objective of this paper is to compare atmospheric, vacuum and pre-drying vacuum frying of apple slices, when using equivalent thermal driving forces, on total oil intake, moisture loss and color development, to understand the differences between both technologies and how they determine main quality attributes.

2. Materials and methods

2.1. Materials

The type of apple used throughout this work is Granny Smith. Apples had an approximate water content of 85% (the exact water content was determined individually for each sample) and were stored at 7 °C and at 85–95% relative humidity. The oil used was Fritomaster frying oil (partially hydrogenated oil: 25% sunflower oil; 75% soy oil) from Watt's (Watt's, Chile).

2.2. Sample preparation

Apples were peeled, washed and cut into 5 mm slices from which 3.8 cm discs were extracted. The apple discs were then immersed in citric acid (5.8%) for 5 s, blanched with boiling water for 1 min and cooled by immersion in cold tap water for 5 min, and drained. Blanched apple discs were either directly fried or vacuum fried, whereas some blanched discs were additionally pre-dried under controlled conditions using a Self-Cooking Center Model SCC661 (Rational, Germany), with dry air at 80 °C, to a final moisture content of 64% w.b., before vacuum frying.

2.3. Frying

Atmospheric and vacuum frying were carried out using the same equipment: an electrically heated, 10-l stainless steel (316L) vessel, which was thermostatically controlled to maintain the set frying temperature ±2 °C using a temperature control system (PID + Fuzzy Logic, Veto, Chile). In both set of experiments, the fryer was filled with 4 l of oil, which was preheated for 2 h prior to frying (Blumenthal, 1991) and discarded after 4 h. Temperature gradients in the oil were minimized by means of a RW20 multi-speed stirrer (IKA®-Labortechnik, Germany) placed in the centre of the oil bath.

2.3.1. Atmospheric deep-fat frying experiments

Five discs per sample were placed inside the frying basket and were covered with a grid to prevent them from floating. Frying was carried out by immersing the basket in the oil, at the set temperature, for 2, 4, 6, 8, 10 and 15 min. After each frying time, the samples were removed from the fryer and hold in a stainless steel grid.

2.3.2. Vacuum frying experiments

Vacuum frying experiments were carried out in the same frying vessel, which was covered with a stainless steel (316L) lid, tightly screwed. The frying vessel was connected to a Speedivac vacuum pump (Edwards Hochvakuum GmbH, Germany) that was adequately separated from the vessel by means of three dry-ice traps, used to prevent water vapor inclusion in the pump oil system.

Once the oil temperature reached the target value, five blanched slices or eight blanched pre-dried slices were placed inside the frying basket, covered with a grid, the lid was fastened and the vessel was depressurized. When the pressure in the vessel achieved 0.15 bar (which corresponds to a water boiling-point of approximately 55 °C), the basket was lowered and immersed in the oil for the required period of time. Thereafter the basket was raised, shaken manually and the vessel was pressurized. Samples were then removed from the fryer and hold in a stainless steel grid, as in atmospheric frying.

2.4. Experimental considerations

No de-oiling system was used in any experiment in order to determine the total oil content absorbed by the samples. Reported results correspond to the arithmetic mean of three batches ± standard deviation. Further, all determinations and measurements on each batch were carried out in triplicate.

In order to compare atmospheric and vacuum frying, equivalent thermal driving forces were used in both processes. The thermal driving force was defined as the difference between the oil temperature and the boiling point of water at the working pressure (that is, 100 °C under atmospheric conditions and 55 °C under vacuum). Three levels of oil temperature were studied: 140, 150 and 160 °C, for atmospheric frying, and 95, 105 and 115 °C, for vacuum frying, providing driving forces (ΔT) equals to 40, 50 and 60 °C.

Frying times were selected in order to work under experimental conditions that ensured containing enough free water in the sample during the immersion period (vigorous water escape), thus permitting understanding oil-uptake and water-loss relationship during the pressurization step and post-frying cooling. In fact, if the sample contains sufficient moisture, the vapor can exert enough pressure (water–vapor pressure) to preclude oil absorption during the immersion period. Conversely, if the food does not contain enough moisture, there is not sufficient pressure build-up to hinder the absorption, allowing oil penetration during the immersion. Since, one of the aims of this work is to study the relationship between these two fractions, it was decided to restrict frying times to those were vigorous water escape occurs, as presented in Section 4.1.

3. Analytical methods

3.1. Oil content

Total oil content of ground apple slices was determined gravimetrically by solvent extraction using the Soxhlet technique (AOAC, 1995), as explained in Bouchon et al. (2003).

3.2. Solids content

Each extracted group was placed in Petri dishes, dried in a forced air oven at 105 °C for 24 h (to constant mass) and cooled in a desiccator (AOAC, 1995).

3.3. Moisture loss

Moisture loss was reported on a dry basis and was calculated from the difference between the original moisture content and the moisture content at time t.

3.4. Color analysis

3.4.1. Image acquisition and capture

The digital image acquisition system consisted of a color 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 color. 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 standardize the illumination level before each session, as explained in Briones and 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.

Images were acquired immediately after frying. Samples were placed in the field of view of the camera and an image of 1600 × 1200 pixels was acquired and stored in JPEG (Joint Photographic Experts Group) format of high resolution and fine quality, in RGB color coordinates.

3.4.2. Color measurement

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

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

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

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

Finally, the color difference between raw (L_0^*, a_0^*, b_0^*) and fried apple slices (L^*, a^*, b^*) was determined taking the Euclidean distance between them, according to Eq. (4):

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

3.5. Statistical analysis

Statistical analysis was done using Statgraphics for Windows software, version 5.0 (Manugistic Inc., USA). Methods applied were analysis of variance, Tukey test and Kruskal-Wallis test with 95% confidence level.

4. Results and discussion

4.1. Moisture loss

Fig. 1 shows the development of moisture loss when frying apple slices at atmospheric conditions and under vacuum either with or without pre-treatment, for the different driving forces used in this study.

Initially, the rate of water loss is high; there is an initial rapid fall of water content mainly due to loss of surface water. In vacuum frying this initial vigorous escape of water is similar to the one obtained under atmospheric conditions, especially when decreasing the driving force. However, for longer frying times, a difference between both technologies is observed. Differences can be partly due to microstructural changes that might occur during the initial depressurization step that might affect water escape, after unbound water surface water is loss. Also, water vapor accumulation in the head space of the fryer might affect moisture loss rate, an effect that can be accentuated at higher thermal driving forces, because of the higher dehydration rate. In pre-dried vacuum fried apples the loss of water is even less vigorous because of the lower amount of water available and because of crust formation during the pre-drying step which imposes initial higher resistance to the escape.

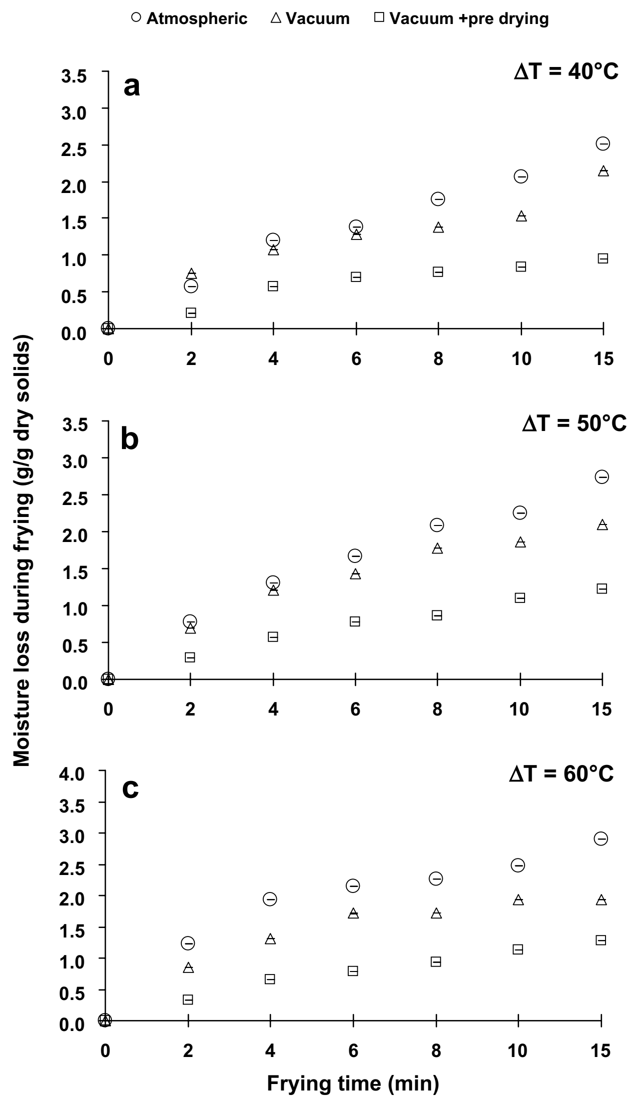

Fig. 1. Effect of frying method and pre-treatment on moisture loss for increasing times when using different thermal driving forces: (a) $\Delta T = 40$ °C, (b) $\Delta T = 50$ °C and (c) $\Delta T = 60$ °C. Points are means ± standard deviation.

4.2. Oil uptake

Fig. 2 shows the development of oil uptake (dry basis) for increasing frying times using different thermal driving forces ($\Delta T = 40$, 50, 60 °C) for atmospheric, vacuum and pre-dried vacuum fried apple slices. The general pattern is an initial rapid increase followed by a gradually decreasing gradient, with a final increase for the longest frying time (15 min).

The statistical analysis showed that the frying method and pre-treatment have a significant effect ($p < 0.05$) in oil uptake (g oil/g dry solids) when analyzing the same driving force. The highest oil absorption is consistently obtained when frying under atmospheric conditions, whereas the

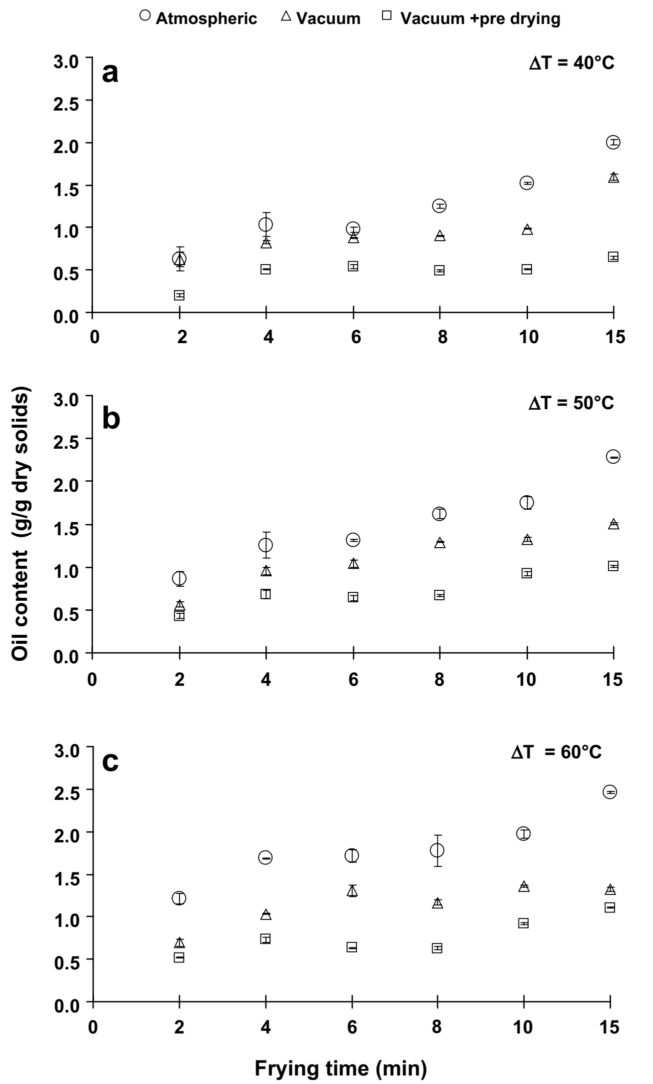

Fig. 2. Effect of frying method and pre-treatment on oil content for increasing times when using different thermal driving forces: (a) $\Delta T = 40$ °C, (b) $\Delta T = 50$ °C and (c) $\Delta T = 60$ °C. Points are means ± standard deviation.

lowest oil absorption is always obtained for pre-dried vacuum fried apples. For instance, after frying for 15 min at $\Delta T = 40$ °C, atmospheric fried slices absorb 21% more oil than vacuum fried slices and more than 3 times, the amount of oil absorbed by pre-dried vacuum fried slices.

When the driving force is increased, the difference in oil uptake between pre-dried vacuum fried and vacuum fried slices decreases at the longest frying time, whereas the difference between the latter and atmospheric frying increases. For instance, after frying for 15 min at $\Delta T = 60$ °C, atmospheric fried slices absorb 47% and 55% more oil than vacuum fried and pre-dried vacuum fried slices, respectively.

The high reduction in oil uptake of pre-dried apple slices is mainly due to crust development and surface changes occurring during the drying step. In effect, crust microstructure development (mean pore size, connectedness and permeability) has a marked effect in oil absorption. In fact, oil absorption is essentially a surface-related phenomenon resulting from the competition between drainage and suction into the porous crust once the food is removed from the oil bath and begins to cool (Bouchon et al., 2003; Moreira et al., 1997; Ufheil & Escher, 1996), and therefore crust permeability is of paramount importance.

Vacuum fried slices suffer slighter structural changes compared to their atmospheric counterpart, an aspect that may well reduce oil uptake. In fact, visual observation showed that the surface of vacuum fried slices was less expanded than the surface of those fried under atmospheric conditions. This can be a direct consequence of the lower vapor-pressure of water in vacuum frying. In addition, higher temperatures (like those involved in atmospheric frying) induce added structural changes, as a consequence of tissue/constituents degradation, which enhance the absorption. In this process, it has been proposed that oil absorption should also occur at the end of the process, and the pressurization step should be critical, because of the rapid increase in pressure to atmospheric values that would force surface oil into the product (Garayo & Moreira, 2002). Consequently, adequate drainage before pressurization is important and certainly a crust with a lower permeability would reduce the uptake.

Moisture loss has long been claimed to be an important factor in oil absorption (Gamble et al., 1987; Pinthus, Weinberg, & Saguy, 1993). In fact, the amount of water removed during the process determines the extent of crust formation, which defines the volume of the final oil reservoir. Certainly, final oil intake would also depend on the oil layer deposited on the surface of the product after the immersion.

Fig. 3 shows oil uptake versus moisture loss results, along with the tendency line obtained using simple regression (linear model), for the different driving forces. Coefficients of determination (R^2 values) for the regressions were 94.91%, 95.33%, and 93.18% for $\Delta T = 40$, 50 and 60 °C, respectively, showing a good relationship between both quantities. This linear relationship shows that traditional observations made for atmospheric deep-fat frying (Gamble et al., 1987) also apply to vacuum frying. This implies that in this set of experiments oil reduction (dry base) in vacuum fried slices would be mainly due to the reduction in moisture loss during the process (for the same frying time) and therefore the water vapor replacement mechanism claimed for atmospheric frying would also apply to vacuum frying. However, this should not be an exclusive factor since compared to atmospheric frying most data points are below the trend line, denoting lower oil contents, implying that oil uptake is additionally impaired.

Interestingly, even though pre-dried vacuum fried slices show low levels of water loss and oil uptake (dots associated to pre-dried vacuum fried slices are located at the lower-bottom part of the trend-line), a positive correlation still exists between both fractions. This relationship can be the expression of an overall reduction of crust permeability during the pre-drying step, which affects both fluxes.

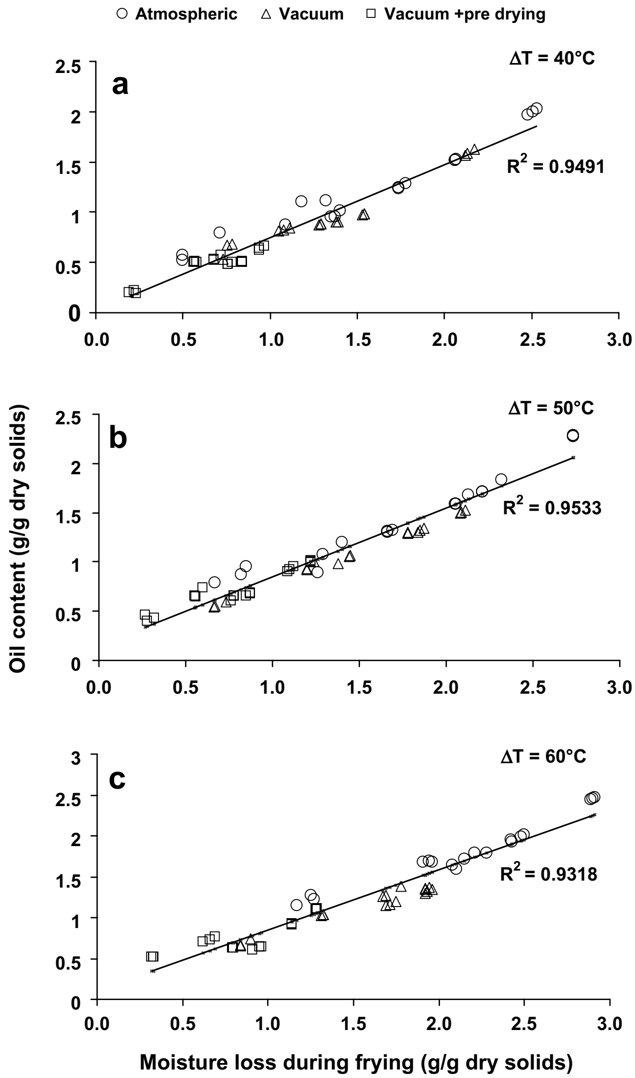

Fig. 3. Oil content versus moisture loss during frying for different thermal driving forces: (a) $\Delta T = 40$ °C, (b) $\Delta T = 50$ °C and (c) $\Delta T = 60$ °C.

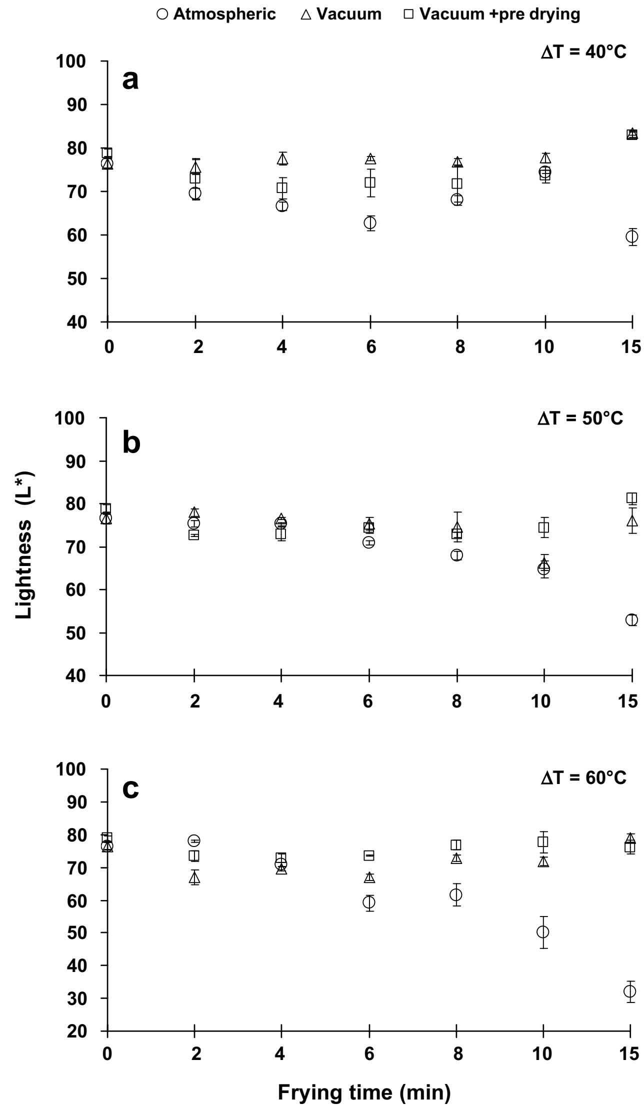

Fig. 4. Effect of frying method and pre-treatment on lightness (L^*) for increasing times when using different thermal driving forces: (a) $\Delta T = 40$ °C, (b) $\Delta T = 50$ °C and (c) $\Delta T = 60$ °C. Points are means ± standard deviation.

Clearly, if the whole loss of water is considered (by adding the amount lost during the pre-drying step), the relationship between both fractions is still maintained. However, associated data points would not follow any more a trend line along with the other two samples, but a new one displaced downwards, making evident the overall reduction in oil uptake.

Finally, it is interesting to note that when the whole set of data is analyzed using simple regression (linear model), a $R^2 = 93.92\%$ is obtained, denoting the good relationship between both fractions.

4.3. Color analysis

Most important changes in color were observed when analyzing L^* (lightness) and a^* (red–green chromaticity) coordinates, which are discussed next.

Fig. 4 shows the change in L^* for the different samples for increasing frying times and driving forces. Overall, L^* values decreased greatly in conventional frying for increasing frying times. For instance, when frying at 160 °C ($\Delta T = 60$ °C), L^* diminished from an initial value of 76.4 (un-fried blanched slices) to a final value, after frying for 15 min, of 32 (much darker). On the other hand, L^* remained nearly constant in vacuum and pre-dried vacuum fried slices, and no significant ($p > 0.05$) differences were found between them when analyzing the whole set of data and when analyzing frying time 10 and 15 min. Besides, L^* values did not differ greatly from raw apple discs ($L_0^* = 86.4$).

L^* is a critical parameter in the frying industry, and is usually used as a quality control factor, therefore its adequate control is of great importance. High L^* values are mainly associated to non-enzymatic browning reactions. These can occur between reducing sugars and amino acids, but also between ascorbic acid, dehydroascorbic acid (oxidized ascorbic acid) or other degradation products from ascorbic-acid oxidation, who enter into Maillard-type browning reactions. Also, the dehydroascorbic acid lactone ring can be irreversibly opened, giving rise to diketogulonic acid, which can be further degraded into several color compounds (e.g. furfural polymers) (Belitz, Grosch, & Schieberle, 2004). Ascorbic acid oxidation is certainly hindered under vacuum, and overall, all chemical reactions are slowed down when the oil temperature is reduced.

Browning reactions had a big impact in red–green chromaticity (a^*). The red–green chromaticity increased considerably in atmospheric frying, changing from negative values (towards green) to positive ones (increasing redness), as shown in Fig. 5.

The final value, obtained after frying for 15 min under atmospheric conditions, was not significantly different ($p > 0.05$) for the different oil temperatures. Vacuum frying did not affect significantly a^* value ($p > 0.05$). It remained mostly negative or near to zero for all samples (vacuum and pre-dried vacuum fried samples), close to the one of a raw apple disc, reflecting the little impact of this technology on the color of the product.

In order to analyze the overall impact of the frying procedure on the color of the product, the color difference between raw (L_0^*, a_0^*, b_0^*) and fried apple slices (L^*, a^*, b^*) was determined according to Eq. (4).

Fig. 6 shows the change in ΔE^* for all samples for increasing frying times and driving forces. In atmospheric frying ΔE^* increased progressively as the frying time increased, enhancing the difference with the raw counterpart. Vacuum and pre-dried vacuum fried slices showed

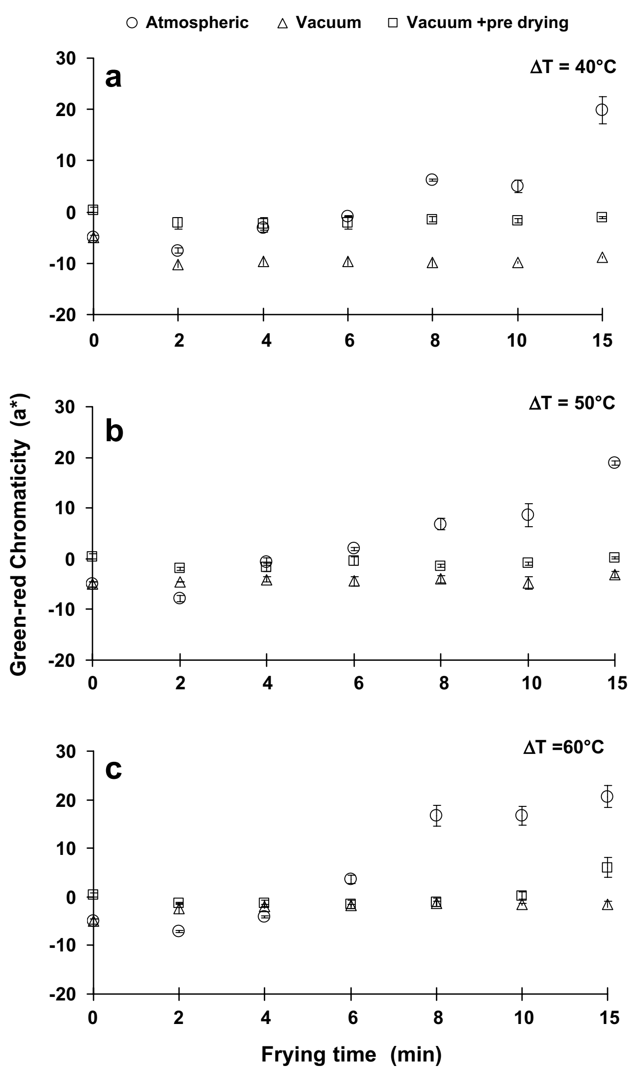

Fig. 5. Effect of frying method and pre-treatment on green–red chromaticity (a^*) for increasing times when using different thermal driving forces: (a) $\Delta T = 40$ °C, (b) $\Delta T = 50$ °C and (c) $\Delta T = 60$ °C. Points are means ± standard deviation.

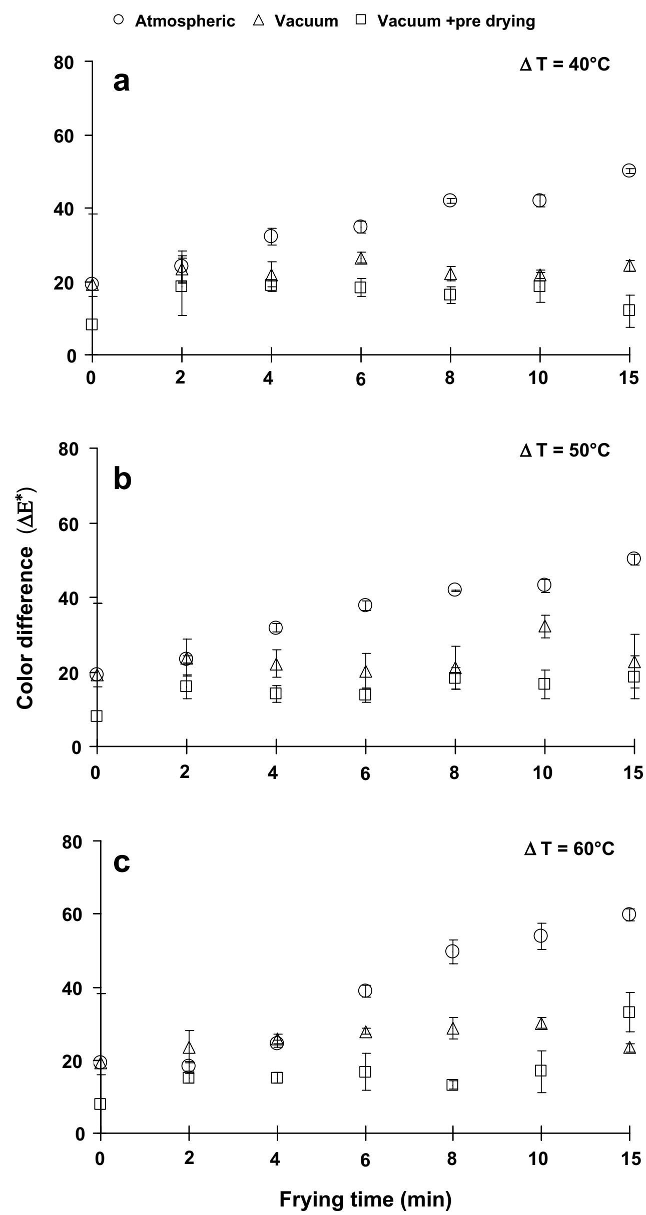

Fig. 6. Effect of frying method and pre-treatment on ΔE^* for increasing times when using different thermal driving forces: (a) $\Delta T = 40$ °C, (b) $\Delta T = 50$ °C and (c) $\Delta T = 60$ °C. Points are means ± standard deviation.

much lower values, which importantly, remained nearly constant for increasing frying times. That is, even though vacuum frying induces changes in color, these changes remain stable for increasing frying times. Lower mean values in ΔE^* were found in pre-dried vacuum fried slices at all temperatures (always below 20), except when frying for 15 min at 115 °C ($\Delta E^* = 33$).

In vacuum fried slices ΔE^* oscillated between 20 and 30, whereas in atmospheric frying ΔE^* achieved values as high as 60. Statistical differences ($p < 0.05$) in ΔE^* were found between atmospheric, vacuum and pre-dried vacuum fried slices when frying at 95 °C ($\Delta T = 40$ °C) and 105 °C ($\Delta T = 50$ °C). Nevertheless, no significant differences were found between the last two when frying at 115 °C ($\Delta T = 60$ °C). However, if the last data point is not considered, the two series are significantly different ($p < 0.05$).

Lower ΔE^* values obtained in pre-dried vacuum fried slices may be due to the lower water activity of these samples as a result of the pre-drying phase, which is particularly low at the surface of the product slowing down non-enzymatic browning. Also, enzymatic residual activity may be further reduced during drying.

5. Conclusions

Vacuum frying was shown to be a promising technique that can be used to reduce oil content in fried apple slices while preserving the color of the product. Particularly, drying prior to vacuum frying was shown to give the best results. The high reduction in oil uptake of pre-dried apple slices was mainly due to crust development and surface changes occurring during the drying step. For instance, when frying was carried out using a driving force of $\Delta T = 60$ °C, pre-dried vacuum fried slices had less than 50% of the oil content sucked by slices fried under atmospheric conditions.

Overall, a strong relationship between water loss and oil content was observed in this set of experiments. This result allows extending observations that have been carried out by other researchers when studying atmospheric frying and implies that in this set of experiments oil reduction in vacuum fried slices would mainly be a consequence of a reduction in moisture loss for the same frying time. Even though pre-dried vacuum fried slices showed low levels of water loss and oil uptake, as a consequence of structural changes, a positive correlation still existed between both fractions. This relationship can be understood in two ways, which can be complementary: it can be thought that the void left by the water escape defines the oil reservoir volume to be occupied by the oil or that both quantities, moisture loss and oil uptake, are the expression of a reduction of crust permeability with a subsequent relationship between both fractions.

In relation to color, most important changes were observed when analyzing L^* (lightness) and a^* (green–red chromaticity) coordinates. Atmospheric frying produced slices that were much darker than vacuum fried slices (lower L^* values) and no significant differences were found between pre-dried vacuum fried and vacuum fried slices. In relation to green–red chromaticity (a^*), traditional fried apples showed a great increase in a^* value for increasing frying times as a consequence of raw-color loss and browning. This was evident when analyzing the overall color difference between raw and fried apple slices (ΔE^*), which increased steadily as time increased during atmospheric frying. On the other hand, apple slices fried under vacuum conditions were lighter and showed only minor changes in ΔE^* for increasing frying times.

References

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

Belitz, H. D., Grosch, W., & Schieberle, P. (2004). *Food chemistry*. Berlin: Springer.

Blumenthal, M. M. (1991). A new look at the chemistry and physics of deep-fat frying. *Food Technology, 45*(2), 68–71.

Bouchon, P., Hollins, P., Person, 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., Aguilera, J. M., & Pyle, D. L. (2003). Structure oil-absorption relationships during deep-fat frying. *Journal of Food Science, 68*(9), 2711–2716.

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*, 87–94.

Browner, W. S., Westenhouse, J., & Tice, J. A. (1991). What if Americans ate less fat? A quantitative estimate of the effect on mortality. *Journal of the American Medical Association, 265*, 3285–3291.

Dobraszczyk, B. J., Ainsworth, P., Ibanoglu, S., & Bouchon, P. (2006). Baking, extrusion and frying. In J. G. Brennan (Ed.), *Food processing handbook* (pp. 237–290). Weinheim: Wiley-VCH.

Fan, L., Zhang, M., & Mujumdar, A. (2005). Vacuum frying of carrot chips. *Drying Technology, 23*, 645–656.

Farkas, B. E., Singh, R. P., & McCarthy, M. J. (1992). Measurement of oil/water interface in foods during frying. In R. P. Singh RP & A. Wirakartakusumah (Eds.), *Advances in food engineering* (pp. 237–245). Boca Raton: CRC Press.

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 UK tubers. *International Journal of Food Science and Technology, 22*, 233–241.

Garayo, J., & Moreira, R. (2002). Vacuum frying of potato chips. *Journal of Food Engineering, 55*, 181–191.

Granda, C., Moreira, R. G., & Tichy, S. E. (2004). Reduction of acrylamide formation in potato chips by low-temperature vacuum frying. *Journal of Food Science, 69*(8), 405–411.

Keller, C., Escher, F., & Solms, J. A. (1986). Method of localizing fat distribution in deep-fat fried potato products. *Lebensmittel-Wissenschaft und Technologie, 19*(4), 346–348.

Kochhar, S. P. (1999). Safety and reliability during frying operations-effects of detrimental components and fryer design features. In D. Boskou & I. Elmadfa (Eds.), *Frying of food* (pp. 253–269). Lancaster: Technomic Publishing.

Krokida, M. K., Oreopolou, V., Maroulis, Z. B., & Marinos-Kouris, D. (2001). Deep fat frying of potato strips – quality issues. *Drying Technology, 19*, 879–935.

Lisinska, G., & Leszczynski, W. (1991). *Potato science and technology*. London: Elsevier Applied Science.

Mintel International Group Ltd. (2006) Salty Snacks – US. Recovery on august, 2006 from: http://www.marketresearch.com.

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.

Moyano, P., Rioseco, V. K., & Gonzalez, P. A. (2002). Kinetics of crust color changes during deep-fat frying of impregnated French fries. *Journal of Food Engineering, 54*, 249–255.

Nonaka, M., Sayre, R. N., & Weaver, M. L. (1977). Oil content of French fries as affected by blanch temperatures, fry temperatures and melting point of frying oils. *American Potato Journal, 54*, 151–159.

Pedreschi, F., & Moyano, P. (2005). Oil uptake and texture development in fried potato slices. *Journal of Food Engineering, 70*, 557–563.

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

Saguy, I. S., Gremaud, E., Gloria, H., & Turesky, R. J. (1997). Distribution and quantification of oil uptake in French fries utilizing a radiolabeled ^{14}C palmitic acid. *Journal of Agriculture and Food Chemistry, 45*(1), 4286–4289.

Shyu, S. L., & Hwang, L. S. (2001). Effects of processing conditions on the quality of vacuum fried apple chips. *Food Research International, 34*, 133–142.

Shyu, S. L., Hau, L. B., & Hwang, L. S. (2005). Effects of processing conditions on the quality of vacuum-fried carrot chips. *Journal of the Science of Food and Agriculture, 85*, 1903–1908.

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

Varela, G. (1988). Current facts about the frying of food. In G. Varela, A. E. Bender, & I. D. Morton (Eds.), *Frying of food: Principles, changes, new approaches* (pp. 9–25). Chichester: Ellis Horwood.

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*, 137–142.