Food Chemistry 119 (2010) 1143–1149

Contents lists available at ScienceDirect

Food Chemistry

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

Vacuum frying reduces oil uptake and improves the quality parameters of carrot crisps

V. Dueik [a], P. Robert [b], P. Bouchon [a,*]

[a] Department of Chemical and Bioprocess Engineering, Pontificia Universidad Católica de Chile, P.O. Box 306, Santiago 6904411, Chile
[b] Department of Food Science and Chemical Technology, Universidad de Chile, P.O. Box 223, Chile

ARTICLE INFO

Article history:
Received 28 April 2009
Received in revised form 30 June 2009
Accepted 20 August 2009

Keywords:
Vacuum frying
Carrot
Oil uptake
Carotenoids
Colour
Crisp
Frying

ABSTRACT

Recent consumer trends towards healthier and low fat products have had a significant impact on the snack industry. The objective of this study was to examine the most important quality parameters of vacuum and atmospheric fried carrot slices in order to identify the specific advantages of vacuum technology. Said parameters include oil uptake, colour changes, and *trans* α and β-carotene degradation. Equivalent thermal driving forces were used (ΔT = 60 °C and 80 °C) to compare the processes, maintaining a constant difference in temperature between the oil and the boiling point of water at the working pressure. The results showed that vacuum frying can reduce oil content by nearly 50% (d.b.) and preserve approximately 90% of *trans* α-carotene and 86% of *trans* β-carotene. This process also allowed for the raw carrot colour to be preserved, which was reflected by good correlations between a^* and *trans* β-carotene content, b^* and *trans* α-carotene content, and hue and total carotenoid content.

1. Introduction

Frying is a complex unit operation that is widely used in the food industry. During the process, food is immersed in an oil bath at a temperature above the boiling point of water. This results in counterflow of water vapour (bubbles) and oil at the surface of the product (Bouchon, Aguilera, & Pyle, 2003). Oil uptake is one of the most important quality parameters of fried food, but this is incompatible with recent consumer trends towards healthier food and low fat products (Bouchon & Pyle, 2004). The consumption of oil and saturated fat in particular is related to significant health problems, including coronary heart disease, cancer, diabetes, and hypertension (Saguy & Dana, 2003). Other undesirable effects derived from the high temperatures involved in the frying process and exposure to oxygen are the degradation of important nutritional compounds and the generation of toxic molecules in the foodstuff or the frying oil itself (Fillion & Henry, 1998). This information has raised a red flag regarding human consumption of fried food. As a result, healthy, low fat snack products have acquired a new level of importance in the snack industry (Moreira, Castell-Perez, & Barrufet, 1999). However, even health-conscious consumers are unwilling to sacrifice organoleptic properties, and intense full-flavour snacks continue to play an important role in the salty snack market (Mariscal & Bouchon, 2008).

Several processes have been developed in order to allow companies to manufacture reduced-fat products that possess the desired quality attributes of deep fat fried food whilst preserving their nutritional properties. These include alternative technologies such as extrusion, drying, and baking, which may be applied to raw food or formulated products. Unfortunately, none of them has been as successful as expected because they are still unable to impart the desired quality attributes of deep fat fried food, such as flavour, texture, appearance, and mouthfeel.

Vacuum frying is a promising technology that may be an option for the production of novel snacks such as fruit and vegetable crisps that present the desired quality attributes and respond to new health trends. This deep frying process is carried out in a closed system under pressures well below atmospheric levels, which makes it possible to substantially reduce the boiling point of water and thus the frying temperature (Garayo & Moreira, 2002). In fact, most of the benefits of this technology are the result of the low temperatures employed and minimal exposure to oxygen. Said benefits include: (i) the reduction of adverse effects on oil quality (Shyu, Hau, & Hwang, 1998), (ii) preservation of natural colour and flavours (Shyu & Hwang, 2001), (iii) decreased acrylamide content (Granda, Moreira, & Tichy, 2004), and (iv) preservation of nutritional compounds (Da Silva & Moreira, 2008).

The oil uptake mechanism of vacuum frying is still not fully understood. During a normal operation, the product is placed inside the frying basket once the oil reaches the target temperature. The lid is then closed and the chamber is depressurised.

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

0308-8146/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.foodchem.2009.08.027

Subsequently, the basket is immersed in the oil bath, where it remains for the required amount of time. It is then lifted out and the vessel is pressurised using a pressure release valve. This results in a sudden increase in the surrounding pressure, which may force the vapour inside of the pores to condense, which means that oil absorption may precede cooling (Garayo & Moreira, 2002). However, as these authors explain, the low pressure may allow air to diffuse faster into the porous structure, obstructing oil passage and leading to lower oil absorption than is observed in atmospheric frying. This hypothesis has been supported by the results of experiments that suggest that vacuum fried potato crisps absorb less than half the oil of crisps fried under atmospheric conditions. In order to compare vacuum and atmospheric frying, Mariscal and Bouchon (2008) defined the term 'equivalent thermal driving force', which is the difference between the oil temperature and the boiling point of water at the working pressure. The authors used several equivalent thermal driving forces (40 °C, 50 °C and 60 °C) when frying apple slices under atmospheric or vacuum conditions (4.4 in. Hg). Their experiments showed that vacuum fried apple slices absorbed slightly less oil, and presented better results for colour preservation than atmospheric fried samples.

Scant information is available on this topic because scientists are only just beginning to perform research in this field. However, it is clear that vacuum frying of non-traditional fruits and vegetables has great potential. In this respect, carrots are an interesting raw material to be studied because they are the most important source of dietary carotenoids. In addition to acting as natural pigments, these compounds have been linked to the prevention of certain types of cancer and degenerative and chronic diseases as well as pro-vitamin A activity (Rodríguez-Amaya, 2001). The processing of foods may cause major carotenoid degradation due to the isomerisation of *trans*-carotenoids, which represent almost 100% of total carotenoid content in raw carrots (Kopas-Lane & Warthesen, 1995), and oxidation, with a subsequent loss of biological activity and colour deterioration (Rodríguez-Amaya, 2001). *Trans–cis* isomerisation affects pro-vitamin A activity, bioavailability, and the antioxidant capacity of carotenoids. Also, there is some evidence that all-*trans*-isomers are absorbed preferentially by humans as compared to *cis* isomers in the case of β-carotene. However, it should be noted that isomerisation is only one of the factors that may determine their bioavailability; carotenoid bioavailability may be enhanced by the food matrix, the interaction between carotenoids, the presence of dietary fat, and processing conditions, particularly mechanical disruption and heat treatment (Schieber & Carle, 2005).

The objective of this study is to compare oil content, moisture loss, *trans* α-and β-carotene retention, and colour development in atmospheric and vacuum deep fat fried carrot crisps made using equivalent thermal driving forces in order to identify the technology's potential for producing novel snacks that present the desired quality attributes whilst reflecting new health trends.

2. Materials and methods

2.1. Sample preparation

Carrots (*Daucus carota cv.* Abaco) were purchased from a local supermarket and stored at 7 °C and 85–95% relative humidity. The carrots were washed and cut into 2 mm-thick slices using a Mandolin Slicer (Danesco International Inc., USA) from which 3.8 cm discs were extracted.

2.2. Frying equipment

Both atmospheric and vacuum frying were carried out using an electrically heated, 10-l stainless steel (316L) vessel covered with a stainless steel (316L) lid, which was thermostatically controlled to maintain the set frying temperature (±2 °C) using a temperature control system (Micro-controller X, model PXR4, Fuji Electric Instruments, Japan). The fryer basket rod was connected to a rotary system, which was used to stir the oil (40 rpm) before frying in order to minimise temperature gradients.

In vacuum frying experiments, the frying vessel was connected to a two-stage high vacuum pump (model DVR-140, Dosivac, Argentina) with the capacity to generate a vacuum up to 1.92 in. Hg (which corresponds to a water boiling point of approximately 38 °C). In order to prevent water vapour from the product from mixing with the oil of the vacuum pump and damaging it, a condenser was installed between the devices. (It consisted of a 4-m stainless steel pipe that was immersed in an ice–water mixture at 0 °C.) In atmospheric frying experiments, the vessel lid was vented by opening a 2 in. metal piece. That piece was tightly affixed to the lid during the vacuum frying experiments.

2.3. Frying conditions

In both sets of experiments, the fryer vessel was filled with 3 l of high-oleic acid sunflower oil (Camilo Ferrón Chile S.A, Chile), which was preheated to 160 °C for 1 h prior to frying and discarded after 3 h of frying.

Equivalent thermal driving forces were used in both processes. The thermal driving force was defined by Mariscal and Bouchon (2008) 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 38 °C for vacuum frying). We used two driving forces (60 °C and 80 °C), which resulted in frying temperatures of 160 °C and 180 °C for atmospheric frying and 98 °C and 118 °C for vacuum frying.

2.3.1. Vacuum frying experiments

Once the oil reached frying temperature, ten carrot slices (~20 g) were placed in the frying basket in order to minimise the drop in temperature. The slices were then covered with a grid to prevent them from floating. The vessel lid was fastened and the vessel depressurised. When the pressure inside the vessel reached 1.92 in. Hg, the basket was immersed in the frying oil for increasing frying times until it reached the bubble-end point. The time required to reach said point varied depending on the frying temperature. After each frying time, the basket was lifted out and left to stand for 3 min and the vessel was pressurised. The samples were then removed from the fryer and allowed to cool to room temperature.

2.3.2. Atmospheric frying experiments

Once the oil reached the frying temperature, ten carrot slices were placed in the frying basket and covered with a grid. The basket was immersed in the frying oil for increasing frying times until it reached the bubble-end point. The time required to reach said point varied depending on the frying temperature. The basket was lifted out and left to stand for 3 min. The samples were then removed from the fryer and allowed to cool to room temperature.

2.4. Experimental considerations

In order to determine the total amount of oil absorbed by the samples, no de-oiling system was used in any experiment. Reported results correspond to the arithmetic mean of three batches ± standard deviation. All batches were handled independently and fresh oil was used for each batch. All determinations and measurements were carried out in triplicate on each batch unless otherwise specified.

3. Analytical methods

3.1. Oil content

Total oil content of ground carrot crisps was determined gravimetrically by Soxhlet extraction with petroleum ether (AOAC, 1995).

3.2. Solids content

Each extracted oil-free sample was placed in a Petri dish, dried in a forced air oven at 105 °C to constant weight, and cooled in a desiccator (AOAC, 1995). Solid content of raw carrot slices was determined using the same procedure.

3.3. Moisture loss

Moisture loss was expressed on a dry basis and calculated using the difference between the original moisture content and the moisture content at time *t*.

3.4. Colour analysis using a computer vision system

A colour digital camera model PowerShot A70 (Canon, USA) connected to a computer *via* USB interface IFC-300PCU (Canon, USA) was mounted on a stand inside a large opaque box with black interior surfaces. The iris was operated using the manual mode, with lens aperture at $f = 8$ and speed 1/3(1/6) (no flash, no zoom) in order to achieve high uniformity and repeatability. The samples were illuminated using four CIE source D65 lamps (60 cm length and 18 W; Model TLD/965, Phillips, Singapore) at 45° angle in order to maximise diffuse reflection, which is responsible for colour. The angle between the camera lens axis and the sample was set at around 90° in an effort to reduce gloss. The camera was grey balanced before each imaging session with a Kodak grey card with 18% reflectance ($L^* = 50$). Afterwards, calibration samples were placed in the camera's view using a white card. A 1600 × 1200 pixel image was acquired and stored in high resolution and superfine quality JEPG (Joint Photographic Experts Group) format in RGB colour coordinates. The RGB colour images were converted to CIELAB or Lab values using Adobe Photoshop 6.0 software (Adobe Systems Inc., USA), which were normalised to L^*, a^*, b^* as explained in Mariscal and Bouchon (2008).

3.5. α and β carotene determination

3.5.1. Carotenoid extraction from raw carrot slices and carrot crisps

Carotenoid content was determined using the methodology described by Robert, Carlsson, Romero, and Masson (2003). Carotenoids were extracted from raw carrot slices by homogenising about 1 g of sample with Celite and cold acetone with a mortar and pestle. The slurry was vacuum filtered and the solid residue was re-extracted with cold acetone. Four extractions were made until no orange colour remained in the solid residue. The combined acetone extracts were transferred into petroleum ether. The organic phase was washed with distilled water to remove residual acetone and filtered through anhydrous sodium sulphate. Then, the solvent of an aliquot of 200 µl was evaporated to dryness under a nitrogen stream. Extracts were dissolved in 1000 µl of acetone prior to analysis by HPLC.

Carotenoids from fried carrot crisps were extracted from about 1 g of ground sample with petroleum ether for 4 h and then vacuum filtered. The extract was made up to 100 ml with petroleum ether and an aliquot of 5 ml was saponified overnight with an equal volume of 10% potassium hydroxide in methanol solution at room temperature. The mixture was poured through a separatory funnel and the carotenoid solution was washed five times with water to remove the alkali. It then was filtered through anhydrous sodium sulphate. The same process was followed for the fresh sample extracts for HPLC analysis.

3.5.2. Preparation of standard solutions

Both all-*trans*-α- and all-*trans*-β-carotene standards were obtained from carrots (*Daucus carota cv.* Abaco). Concentrations of standards in petroleum ether were determined by spectrophotometry using their respective $A^{1\%}_{1cm}$ (Rodríguez-Amaya, 2001). Calibration curves were obtained for each carotenoid, diluting standard solutions and measuring associated peaks with HPLC.

3.5.3. Chromatographic procedure

Carotenoid analysis was carried out by HPLC using a Waters symmetry column (C18, 5 µm particle size, 4.6 mm i.d × 25 cm; Waters, USA). An isocratic mobile phase of methanol:acetonitrile:ethyl acetate (20:65:15 by vol) was used at a rate of 1 ml/min. The HPLC system consisted of a Merck-Hitachi L-6200 pump and a Waters 996 Photodiode Array detector, which were hooked up to a computer with Millennium 32 software. Carotenoids were detected at 450 nm and identified by comparing peak retention times with standards. *Cis*-β-carotene appeared as a peak following its *trans*-isomer.

3.5.4. α and β carotene retention

The absolute retention factor of each carotenoid was expressed according to Fillion and Henry (1998) on a dry-weight fat free basis as follows:

$$\text{Absolute retention} = \frac{\text{nutrient content per g cooked food}}{\text{nutrient content per g raw food}} \times (\text{dry weight, fat free}) \cdot 100 \quad (1)$$

3.6. Water activity (a_w) determination

The a_w of vacuum and atmospheric fried carrot crisps was measured using a Lufft aw-wert-Messer (Durotherm, Germany) at 20 °C.

3.7. Texture

The texture of the fried carrot crisps was analysed using the procedure described by Da Silva and Moreira (2008), which consists of a three-point bending test. The sample was supported using two parallel edges in order to apply the load centrally. The system was mounted in a TA.XT2 Texture Analyser (Texture Technologies Corp., USA) using a support span of 16 mm. A 2.5 mm-thick steel blade with flat edge was used to fracture the sample at a constant rate of speed of 10 mm s^{-1}. The force (N) at the fracture point (highest value in the plot) was used as the resistance to breakage.

3.8. Statistical analysis

Statistical analysis was executed using Statgraphics 5.0 software (Manugistic Inc., USA). One-way variance analysis was carried out in order to confirm that there were no significant differences amongst fried sample measurements under specific conditions. Disparities between samples fried under different conditions were determined through confidence interval analysis using the Bonferroni test. All significant differences were determined with a confidence level of 95%. Linear correlation of colour parameters and carotenoid content was also examined by carrying out a linear regression between a specific colour parameter and

carotenoid content (total carotenoids, *trans* α-carotene, or *trans* β-carotene content). Then, the coefficient of determination (r^2) for the linear regression model was calculated.

4. Results and discussion

4.1. Moisture loss

Fig. 1 shows moisture loss for each frying time during vacuum and atmospheric frying of carrot slices using thermal driving forces of 60 °C and 80 °C. The loss of moisture during vacuum and atmospheric frying presented a classical drying profile. There was an initial rapid decrease in water content, which was mainly due to the loss of surface and unbound inner water, followed by a gradually decreasing gradient due to crust formation.

All samples were dried to the same final moisture content (bubble-end point, ~2% w.b.) The frying temperature and technology (pressure) significantly affected the rate of moisture loss and the time required to achieve the desired level of dehydration (see Fig. 1). Samples fried under atmospheric conditions using a thermal driving force of 80 °C achieved bubble-end point after 2 min, whilst samples fried under vacuum conditions needed 3 min. Something similar was observed when the samples were fried using a thermal driving force of 60 °C. Samples fried under atmospheric and vacuum conditions needed 3 and 5 min, respectively, to achieve bubble-end point. The differences are thought to be mainly associated with micro-structural changes. Though the same thermal driving force is used in both processes, samples fried under vacuum conditions are exposed to lower temperatures. As a result, micro-structural changes/damage are impaired. (This is one of the main advantages of vacuum technology.) Also, during the initial depressurisation step of vacuum frying, micro-structural surface changes may occur, which may prevent water from escaping. Furthermore, even though dehydration is mainly limited by heat transfer, diffusion may play a role. Diffusion slows down at lower temperatures, a factor that may preclude moisture loss. Similar results were found by Mariscal and Bouchon (2008) when frying apple slices.

4.2. Oil absorption

Fig. 2 shows the evolution of the oil uptake of carrot crisps for increasing atmospheric and vacuum frying times using thermal driving forces of 60 °C and 80 °C. The general pattern of oil uptake shows an initial rapid increase followed by a gradually decreasing gradient, with a considerable amount absorbed during the initial period. There were great differences between samples fried under atmospheric and vacuum conditions and between those fried using different thermal driving forces.

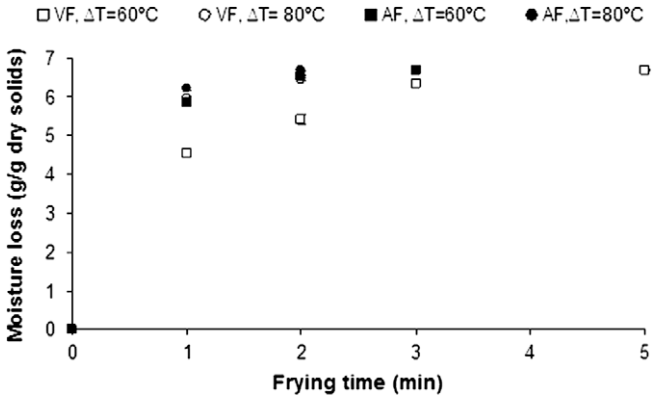

Fig. 1. Moisture loss during atmospheric (AF) and vacuum frying (VF) of carrot crisps when using thermal driving forces of 60 °C ($T_{oil\ (VF)}$ = 98 °C and $T_{oil\ (AF)}$ = 160 °C) and 80 °C ($T_{oil\ (VF)}$ = 118 °C and $T_{oil\ (AF)}$ = 180 °C). Points are means ± standard deviations.

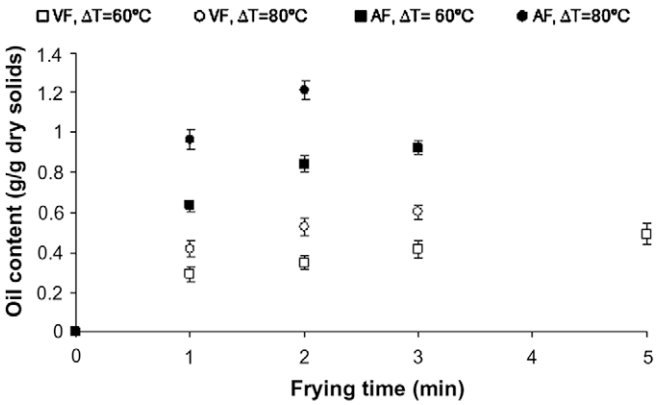

Fig. 2. Oil uptake during atmospheric (AF) and vacuum frying (VF) of carrot crisps when using thermal driving forces of 60 °C ($T_{oil\ (VF)}$ = 98 °C and $T_{oil\ (AF)}$ = 160 °C) and 80 °C ($T_{oil\ (VF)}$ = 118 °C and $T_{oil\ (AF)}$ = 180 °C). Points are means ± standard deviations (n = 3).

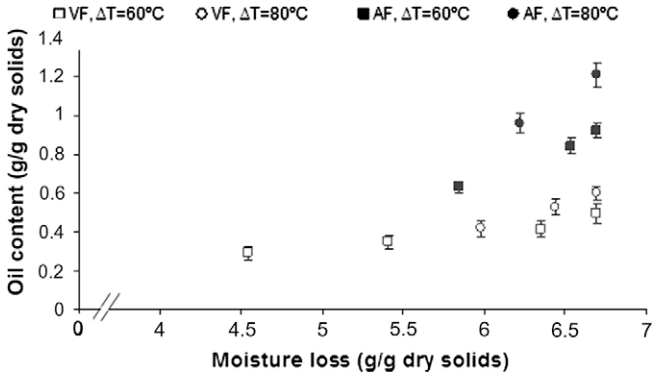

Fig. 3. Oil content versus moisture loss during atmospheric (AF) and vacuum frying (VF) of carrot crisps when using thermal driving forces of 60 °C ($T_{oil\ (VF)}$ = 98 °C and $T_{oil\ (AF)}$ = 160 °C) and 80 °C ($T_{oil\ (VF)}$ = 118 °C and $T_{oil\ (AF)}$ = 180 °C). Points are means ± standard deviations (n = 3).

Oil absorption has long been claimed to be 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; Gamble, Rice, & Selman, 1987; Moreira, Sun, & Chen, 1997). Consequently, oil absorption is heavily linked to moisture loss since it determines the extent of crust formation and therefore the volume that is available for oil infiltration. Fig. 3 shows oil uptake versus moisture loss during vacuum and atmospheric frying of carrot slices. The strong relationship between them suggests that the water vapour replacement mechanism, which is said to occur during atmospheric frying, would also take place during vacuum frying, as determined by Mariscal and Bouchon (2008). Statistical analysis showed that both the frying method and the thermal driving force had a significant effect ($p < 0.05$) on oil uptake (g oil/g dry solids) for the same dehydration level. In fact, vacuum fried carrot slices absorbed 47% and 50.5% (d.b.) less oil than atmospheric fried ones at bubbled-end point when using thermal driving forces of 60 °C and 80 °C, respectively. When comparing vacuum fried carrot crisps, those fried using a thermal driving force of 60 °C absorbed a significantly lower amount of oil compared to those fried using a thermal driving force of 80 °C. These results concur with those

obtained by Garayo and Moreira (2002), who determined that the oil content of vacuum fried potato crisps (37% d.b.) was significantly lower than that of potato crisps fried under atmospheric conditions (66% d.b.) The authors explained that during a normal vacuum frying operation, the product is removed from the oil bath and the vessel is vented before cooling takes place. This results in a sudden increase in the surrounding pressure at a constant temperature, which may force the vapour inside of the pore to condense, decreasing P_{pore} and therefore initiating oil absorption before cooling begins (that is, $P_{surroundings} - P_{pore} > 0$). They further explain that, because of the low pressure, air may diffuse faster into the porous space, obstructing oil passage and therefore leading to a reduction in oil uptake in vacuum fried snacks as compared to atmospheric fried ones. Mariscal and Bouchon (2008) also observed lower oil uptake in vacuum fried apple crisps than in atmospheric fried ones. They attributed this to the lower vapour-pressure of water during vacuum frying and to the higher temperatures reached during atmospheric frying, which induce added structural changes like tissue/constituents degradation. However, the decrease was less pronounced in apples than in carrot slices. This is probably due to the high porosity of apples.

4.3. Carotenoid content

The most abundant carotenoid found in fresh and fried carrot samples was *trans* β-carotene, which represents about 60% of total carotenoid content. The second-most abundant was *trans* α-carotene, which accounts for nearly 40%. These results are in agreement with the literature that has reported that *trans* β-carotene content ranges from 60% to 80%, whereas *trans* α-carotene content ranges from 10% to 40% (Chen, Peng, & Chen, 1995).

Table 1 shows absolute retention of *trans* α- and *trans* β-carotene after vacuum and atmospheric frying of carrot slices using thermal driving forces of 60 °C and 80 °C. A thermal driving force of 60 °C during vacuum frying results in minor degradation of both *trans* α- and *trans* β-carotene (only 10.5% and 13.6% degradation, respectively). When the thermal driving force was increased (ΔT = 80 °C), absolute retention was about 60%, which is still much higher than the absolute retention found in atmospheric fried crisps.

Thermal processing may result in losses of all-*trans*-carotenes and the formation of *cis* isomers. In fact, a reduction in the percentage of all-*trans*-β-carotene with the concomitant increase of 13-*cis* and 9-*cis* isomers has been observed during processing (Chandler & Schwartz, 1988). Losses of all-*trans*-α- and all-*trans*-β-carotene were greater during atmospheric frying, probably as a result of their isomerisation at elevated temperatures. In fact, formation of 13-*cis*-β-carotene was observed in carrot crisps fried at 160 °C and 180 °C, representing 12.5 ± 1.1% and 28.6 ± 1.4% of total carotenes, respectively. Chandler and Schwartz (1988) noted that *cis* isomers could account for as much as 29% of total β-carotene content in processed sweet potatoes. *Trans–cis* isomerisation affects pro-vitamin A activity and the antioxidant capacity of carotenoids. In addition, β-carotene all-*trans*-isomer is absorbed preferentially by humans compared to *cis* isomer (Schieber & Carle, 2005).

Our results suggest that *trans* β-carotene degradation is faster than *trans* α-carotene degradation in all frying conditions. The degradation rate of carotenoids depends on their structure. Key aspects are the number of double bonds and the maximum overlap of carbon–carbon double bond molecular orbitals, which give the highest susceptibility (Miller, Sampson, Candeias, Bramley, & Rice-Evans, 1996). Both *trans* α- and *trans* β-carotene have 11 double bonds. Their structural difference lies in the cyclisation of their ends: *trans* β-carotene has one β-ring on each side of the molecule whereas *trans* α-carotene has one β-ring and a ε-ring. Steric hindrance reduces the orbital overlap between the chain double bonds and the β-ring double bonds in the molecules of *trans* α- and *trans* β-carotene. This leaves *trans* β-carotene with 9 fully overlapping double bonds plus 2 β-ring double bonds with reduced overlap, and *trans* α-carotene with 9 fully overlapping double bonds plus only one β-ring conjugated double bond, as the double bond of the ε-ring is not part of the conjugated double bond system (Anguelova & Warthesen, 2000). Thus, *trans* β-carotene has a higher susceptibility to oxidation and isomerisation because it has 11 conjugated double bounds, whereas *trans* α-carotene only has 10.

4.4. Colour development

Carrots' colour is largely related to the presence of carotenes. As reported by Sulaeman et al. (2001), the orange colour of carrots and carrot crisps can be described by lightness (L^*), redness (a^*), yellowness (b^*), and Hue parameters. Table 2 shows changes in L^*, a^* and b^* values of carrot crisps for increasing frying times during atmospheric and vacuum frying. Hue values are not included since we did not find a significant relationship between this parameter and processing conditions.

L^* is a critical parameter in the frying industry as it is usually the first quality attribute evaluated by consumers when determining product acceptance. Low L^* values indicate a dark colour and are mainly associated with non-enzymatic browning reactions. As shown in Table 2, L^* value decreased significantly during atmospheric frying for both thermal driving forces. For instance, L^* value diminished from L_0^* = 65.2 to L^* = 34.2 at bubble-end point (much darker) when frying at 180 °C. On the other hand L^* remained nearly constant during vacuum frying, only decreasing to L^* = 58.4 and L^* = 55.9 when using thermal driving forces of 60 °C and 80 °C, respectively.

The degradation of *trans* α- and *trans* β-carotene had a big impact on a^* and b^* values, as shown in Table 2. Crisps fried under vacuum conditions using a thermal driving force of 60 °C maintained their orange-yellow chromaticity, showing a slight decrease in their colour coordinates, which varied from a_0^* = 49.9 to a^* = 45.4 and from b_0^* = 65.4 to b^* = 65.1. Carrot slices fried under atmospheric conditions showed a significant decrease in their colour coordinates, reaching final values of a^* = 15.3 and b^* = 25.3, when frying at 180 °C. Our results correspond to those of Shyu,

Table 1
Trans α and *trans* β-carotene absolute retention, water activity and kinetic constants of textural changes during vacuum and atmospheric frying of carrot crisps when using thermal driving forces of 60 °C ($T_{oil\ (VF)}$ = 98 °C and $T_{oil\ (AF)}$ = 160 °C) and 80 °C ($T_{oil\ (VF)}$ = 118 °C and $T_{oil\ (AF)}$ = 180 °C).

Frying pressure (inch Hg)	Thermal driving force (°C)	*Trans* α-carotene absolute retention at bubble-end point (%)	*Trans* β-carotene absolute retention at bubble-end point (%)	Water activity at bubble-end point	Texture kinetic constants	
					Softening kinetic constant k_s (s^{-1})	Hardening kinetic constant k_h (s^{-2})
1.92	60	89.5 ± 2.5	86.4 ± 4.3	0.442 ± 0.015	1.8582	0.0441
	80	60.4 ± 1.7	58.6 ± 3.0	0.452 ± 0.01	1.9655	0.1209
29.92	60	35.7 ± 1.4	31.6 ± 1.8	0.439 ± 0.015	3.5218	0.1322
	80	33.9 ± 1.3	27.9 ± 1.5	0.436 ± 0.012	4.1194	0.2775

Table 2
Evolution of lightness (L^*), green–red chromaticity (a^*) and blue–yellow chromaticity (b^*) during atmospheric (AF) and vacuum frying (VF) of carrot crisps when using thermal driving forces of 60 °C ($T_{oil\ (VF)}$ = 98 °C and $T_{oil\ (AF)}$ = 160 °C) and 80 °C ($T_{oil\ (VF)}$ = 118 °C and $T_{oil\ (AF)}$ = 180 °C).

Colour coordinate	Frying pressure (in. g)	Thermal driving force (°C)	Frying time (min)				
			0	1	2	3	5
L^*	1.92	60		62.6 ± 0.7	60.7 ± 1.1	59.1 ± 1.7	58.4 ± 1.8
		80	65.2 ± 0.47	61.1 ± 0.7	59.3 ± 1.7	55.9 ± 0.7	–
	29.92	60		55.5 ± 1.3	47.9 ± 0.8	43.1 ± 0.8	–
		80		52.4 ± 1.6	34.2 ± 1.0	–	–
a^*	1.92	60		47.8 ± 1.5	46.7 ± 2.5	45.9 ± 2.5	45.4 ± 2.2
		80	49.9 ± 1.0	48.1 ± 1.9	45.9 ± 2.4	37.1 ± 3.2	–
	29.92	60		45.2 ± 1.9	38.1 ± 2.8	24.9 ± 2.0	–
		80		34.4 ± 3.3	15.3 ± 3.9	–	–
b^*	1.92	60		64.0 ± 3.5	63.1 ± 3.2	64.1 ± 2.5	65.1 ± 2.5
		80	65.4 ± 0.64	62.3 ± 2.6	61.5 ± 2.7	60.1 ± 3.5	–
		60		62.8 ± 1.3	53.6 ± 0.9	41.8 ± 3.1	–
		80		61.0 ± 1.4	25.3 ± 2.0	–	–

Hau, and Hwang (2005), who reported that the values of a^* and b^* decrease significantly as the frying temperature increases above 100 °C because of carotenoids' instability. In fact, we found good linear correlations between a^* and *trans* β-carotene content (r^2 = 0.95), b^* and *trans* α-carotene content (r^2 = 0.78) and hue and total carotenoids content (r^2 = 0.91) when comparing values of fried crisps at bubble-end point.

4.5. Water activity (a_w)

As shown in Table 1, samples reached a water activity (a_w) average value of approximately 0.44. This value matches the results obtained by Katz and Labuza (1981), who found that potato crisps' sensory acceptability decreases markedly above a critical value of 0.47. Furthermore, no significant differences were found amongst the samples.

Water activity affects the stability of dehydrated foods because it determines both chemical reaction rates and microbial activity. The limiting value of a_w for the growth of any microorganism is around 0.6. Below this value, food spoilage is mainly due to enzymatic and chemical reactions, such as oxidation (Adams & Moss, 1995). The rate of oxidation may rise as water content increases since water can enhance reactant mobility and bring catalysts into solution. In relation to carotenoid stability. Lavelli, Zanoni, and Zaniboni (2007) showed that both *trans* α- and β-carotene from dehydrated carrots present their maximum stability at a_w values between 0.34 and 0.54. These results confirm previous findings by other authors (Baloch, Buckle, & Edwards, 1977).

4.6. Texture

Frying of raw vegetables induces major changes in their microstructure, which in turn determine their final physical and sensory properties. The most important textural attribute of crisps and chips is crispness, which denotes freshness and high quality. A crisp should be firm and snap easily when bent, emitting a crunchy sound (Krokida, Oreopoulou, Maroulis, & Marinos-Kouris, 2001).

During frying, vegetable tissues show an initial softening that is followed by hardening due to the progressive development of a dehydrated crust. In order to incorporate both phenomena, Pedreschi and Moyano (2005) modelled textural changes (normalised maximum force) during frying by means of two terms (see Eq. (2)). The first describes the softening of the tissue for short frying times (fast phase) and the second describes a hardening dependent component (slow phase), which is a function of the square of the frying time and gains relevance at longer frying times.

$$MF^* = e^{-k_s \cdot t} + k_h \cdot t^2 \quad (2)$$

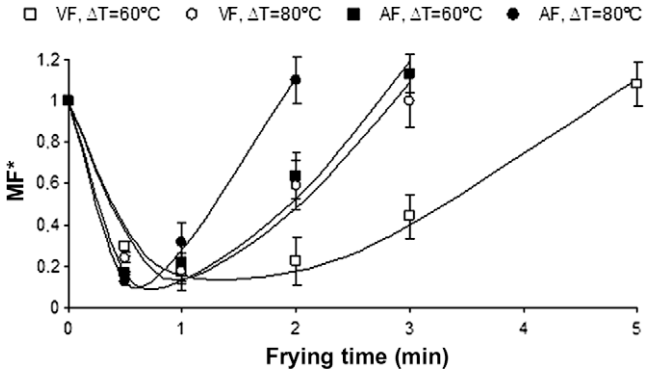

Fig. 4. Textural changes during atmospheric (AF) and vacuum frying (VF) of carrot crisps when using thermal driving forces of 60 °C ($T_{oil\ (VF)}$ = 98 °C and $T_{oil\ (AF)}$ = 160 °C) and 80 °C ($T_{oil\ (VF)}$ = 118 °C and $T_{oil\ (AF)}$ = 180°C). Points are means ± standard deviations (n = 10). Continuous lines represent the model from Eq. (2).

where MF^* = normalised maximum force; k_s = kinetic constant for softening of carrot tissue during frying (s^{-1}); k_h = kinetic constant for the crust hardening process during frying (s^{-2}) and t = frying time (min).

The final maximum force (MF) of fried carrot crisps was not affected by the frying technology and the thermal driving force used. All samples reached final values of between 5.01 and 5.68 N. Nevertheless, the frying technology significantly affected the rate of softening and hardening. For instance, when using a thermal driving force of 60 °C, k_s values were 1.8582 and 3.5218 s^{-1} and k_h values were 0.0441 and 0.1322 s^{-2} when frying under vacuum and atmospheric conditions, respectively. Also, higher frying temperatures resulted in faster softening of the tissue and subsequent hardening (see Table 1 and Fig. 4).

5. Conclusions

Vacuum-fried carrots may be a promising snack category due to the fact that carrots are the most important source of dietary carotenoids, and this technology makes it possible to overcome major carotenoid degradation pathways due to isomerisation and oxidation and thus preserve biological activity. The results showed that vacuum fried crisps (driving force of 60 °C) may reduce the oil content of carrot crisps by nearly 50% (d.b.) compared to atmospheric fried crisps produced using the same driving force. Furthermore, they preserve around 90% of *trans* α-carotene and 86% *trans* β-carotene, which leads to the preservation of the colour of raw carrots. This is reflected by L^*, a^*, b^* colour coordinate analyses,

excellent linear correlations between a^* and *trans* β-carotene content ($r^2 = 0.95$), b^* and *trans* α-carotene content ($r^2 = 0.78$), and hue and total carotenoids content ($r^2 = 0.91$) when comparing values of fried crisps at bubble-end point. As a result, vacuum frying may be a useful process in the production of novel snacks that present desired quality attributes and respond to new health trends.

Acknowledgements

The authors appreciate the financial support received through FONDECYT Project No. 1070764 and Grants from Conicyt and the PUC School of Engineering.

References

Adams, M. R., & Moss, M. O. (1995). *Food microbiology*. Cambridge: The Royal Society of Chemistry.

Anguelova, T., & Warthesen, J. (2000). Degradation of lycopene, α-carotene, and β-carotene during lipid peroxidation. *Journal of Food Science, 65*(1), 71–75.

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

Baloch, A. K., Buckle, K. A., & Edwards, R. A. (1977). Stability of β-carotene in model systems containing sulphite. *Journal of Food Technology, 12*, 309–316.

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

Bouchon, P., & Pyle, D. L. (2004). Studying oil absorption in restructured potato chips. *Journal of Food Science, 69*, E115–E122.

Chandler, L. A., & Schwartz, S. J. (1988). Isomerization and losses of trans-beta-carotene in sweet potatoes as affected by processing treatments. *Journal of Agricultural and Food Chemistry, 36*, 129–133.

Chen, B. H., Peng, H. Y., & Chen, H. E. (1995). Changes of carotenoids, color, and vitamin A content during processing of carrot juice. *Journal of Agricultural and Food Chemistry, 43*, 1912–1918.

Da Silva, P., & Moreira, R. (2008). Vacuum frying of high-quality fruit and vegetable-based snacks. *Lebensmittel – Wissenschaft und Technologie, 41*(10), 1758–1767.

Fillion, L., & Henry, C. J. K. (1998). Nutrient losses and gains during frying: A review. *International Journal of Food Sciences and Nutrition, 49*(2), 157–168.

Gamble, M. H., Rice, P., & Selman, J. D. (1987). Distribution and morphology of oil deposits in some deep fried products. *Journal of Food Science, 52*, 1742–1743.

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

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

Katz, E. E., & Labuza, T. P. (1981). Effect of water activity on the sensory crispness and mechanical deformation of snack food products. *Journal of Food Science, 46*, 403–409.

Kopas-Lane & Warthesen (1995). Carotenoids photostability in raw spinach and carrots during cold storage. *Journal of Food Science, 60*, 773–776.

Krokida, M. K., Oreopoulou, V., Maroulis, Z. B., & Marinos-Kouris, D. (2001). Effect of pre-treatment on viscoelastic behaviour of potato strips. *Journal of Food Engineering, 50*, 11–17.

Lavelli, V., Zanoni, B., & Zaniboni, A. (2007). Effect of water activity on carotenoids degradation in dehydrated carrots. *Food Chemistry, 104*, 1705–1711.

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

Miller, N. J., Sampson, J., Candeias, L. P., Bramley, P. M., & Rice-Evans, C. A. (1996). Antioxidant activities of carotenes and xanthophylls. *FEBS Letters, 384*, 240–242.

Moreira, R., Castell-Perez, M. E., & Barrufet, M. A. (1999). *Deep-fat frying: Fundamentals and applications*. Gaithersburg, MD: Aspen Publishers Inc..

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

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

Robert, P., Carlsson, R. M., Romero, N., & Masson, L. (2003). Stability of spray-dried encapsulated carotenoid pigments from Rosa Mosqueta (*Rosa rubiginosa*) Oleoresin. *Journal of the American Oils Chemical Society, 80*(11), 1–6.

Rodríguez-Amaya, D. (2001). *A guide to carotenoid analysis in foods*. <http://www.ilsi.org/file/carotenoid.pdf>. [ISBN 1-57881-072-8].

Saguy, S., & Dana, D. (2003). Integrated approach to deep fat frying: Engineering, nutrition, health and consumer aspects. *Journal of Food Engineering, 56*, 143–152.

Schieber, A., & Carle, R. (2005). Occurrence of cis-isomers in food: Technological, analytical, and nutritional implications. *Trends in Food Science and Technology, 16*, 416–422.

Shyu, S., Hau, L., & Hwang, L. (1998). Effect of vacuum frying on the oxidative stability of oils. *Journal of the American Oils Chemical Society, 75*(10), 1393–1398.

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

Shyu, S., & Hwang, L. (2001). Effect of processing conditions on the quality of vacuum fried apple chips. *Food Research International, 34*(2–3), 133–142.

Sulaeman, A., Keeler, L., Taylor, S. A., Giraud, D. W., Taylor, S. L., Wehling, R. L., et al. (2001). Carotenoid content and physicochemical and sensory characteristics of carrot chips deep-fried in different oils at several temperatures. *Journal of Food Science, 66*(9), 1257–1264.