The effect of a de-oiling mechanism on the production of high quality vacuum fried potato chips

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**ABSTRACT**

Ways of removing the adhered surface oil, while the product is still in the fryer, has been the subject of many studies and patents for deep-fat frying processes. In the case of vacuum frying, this problem is exacerbated by the pressurization step, which causes a quick increase in pressure in the pore space thus forcing most of the surface oil into the product pore spaces. Therefore, for vacuum frying, a de-oiling mechanism is required to reduce the excessive oil absorption at the surface of the product. The main objective of this study was to establish the effect of de-oiling and frying temperature on potato chips quality attributes and oil absorption.

Potato slices (30 g, 1.6 mm thick, 5 cm diameter) were fried for 360 s in a lab-scale vacuum fryer (P < 1.33 kPa (10 Torr); 8 L of fresh oil) at 120, 130, and 140 °C. A centrifuging system (750 rpm (63g units) for 40 s) was used before pressurizing the vessel and its effect on the final oil content (FOC) and product quality attributes were evaluated using standard methods.

Samples fried at 120 °C for 360 s (non-centrifuged) had a final oil content of 0.43 g/g product compared to 0.097 g/g product for the centrifuged ones. Most of the oil was absorbed in the product during first 180 s of frying; and by the end of frying only 14% of the total oil content (TOC) was internal oil (IOC) while 86% was surface oil (SOC). About 34% of the IOC and only 0.7% of the SOC was absorbed during the first 20 s of frying.

Oil content absorption kinetics increased exponentially during the first 120 s of frying followed by a slight drop until the end of frying. At the end of frying, bulk density and porosity values of the non-centrifuged samples were around 800 kg/m$^3$ and 0.36 and 564 kg/m$^3$ and 0.61 for the centrifuged samples, respectively. No significant changes ($P < 0.05$) were observed in moisture loss, shrinkage, color, and texture for the two treatments.

Experimental data for color and oil distribution with temperature can be accurately predicted using a special case of the logistic model. The kinetics of oil distribution and porosity with temperature can be described using the fractional conversion exponential model.

Vacuum frying with a de-oiling step produces superior quality fried products with lower oil content.© 2008 Elsevier Ltd. All rights reserved.

1. Introduction

In vacuum frying operations, food is heated under reduced pressure (<6.67 kPa (50 Torr)) causing a reduction in the boiling point of the oil and the moisture in the foods. It is an efficient method to produce fruit and vegetable snacks with the necessary degree of dehydration without excessive darkening or scorching (Moreira et al., 1999). Vacuum frying is excellent to maintain product’s nutritional quality (phytochemicals), the color is enhanced (less oxidation) (Da Silva and Moreira, 2008), and it reduces oil degradation. However, a de-oiling mechanism is necessary to remove the excessive oil absorption at the surface of the product.

Perez-Tinoco et al. (2008) produced high quality pineapple chips by vacuum frying the fresh product at 24 kPa for 120 °C for 7 min. The chips had a golden yellow color with low oil content (18% w.b.), high residual content of vitamin C, presence of phenolic compounds, and antioxidant capacity.

Da Silva and Moreira (2008) observed that mango, blue potato chips, green beans, and sweet potato chips fried under atmospheric conditions were of lower quality than the products fried under vacuum (1.33 kPa and 120 °C), though texture characteristics of the fried products were not affected by the frying method. Anthocya-nin (mg/100g d.b.) of vacuum fried blue potato chips was 60% higher. Final total carotenoids (mg/g d.b.) was higher by 18% for green beans, 19% for mango chips, and by 51% for sweet potato chips. Sensory panelists overwhelmingly preferred ($P < 0.05$) the vacuum fried products for color, texture, taste, and overall quality. Most of the products retained or accentuated their original colors.
when fried under vacuum. The traditional fried products showed excessive darkening and scorching.

Garayo and Moreira (2002) used paper towels to remove the excess of oil at the surface of potato chips after the product was removed from the fryer. They concluded that vacuum frying (~3.12 kPa) could produce potato chips with lower oil content (30% less) and the same texture and color characteristics of those fried in conventional (atmospheric) fryers. They observed that one major difference between potato slices fried under vacuum and atmospheric conditions was the surface structure of the potato chips formed during the process. A vacuum fried potato chips had less expansion and the surface had numerous small bubbles, as opposed to a potato chips fried under atmospheric pressure.

The bubble formation at the product’s surface is the result of gas expansion inside the pores. For vacuum fried chips, once the fryer is evacuated, the water vapor in the pores expands with little resistance (since the crust has not been formed and/or starch gelatinized) even before the product is fried. During frying, little expansion may be produced by the superheated vapor trying to escape the pore space. For the chips fried under atmospheric conditions, the expansion happens when the product is immersed in the oil. Water is heated first and then the vapor expanded. As it is heated, starch will gelatinize producing a barrier for the saturated vapor to escape (Kawas and Moreira, 2001). As a result, large, but few, bubbles will be formed at the chips surface.

Mariscal and Bouchon (2008) observed that drying prior to vacuum frying (5.37 kPa) produce apple chips with lower oil content compared to atmospheric frying. 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.

Da Silva and Moreira (2008) showed that the oil content of vacuum fried (1.33 kPa) sweet potato chips and green beans was 24% and 16% lower compared to traditionally fried products, respectively. However, vacuum fried blue potato and mango chips had 6% and 5% more oil, respectively, than the traditional fried samples. They used the same approach, as described by Garayo and Moreira (2002) above, to remove the oil content from the products surface. These results clearly indicate that product characteristics, and texture developed during frying, can affect the final oil content of the product.

Oil absorption is a complex phenomenon that happens mostly when the product is removed from the fryer during the cooling stage (Moreira et al., 1999). Garayo and Moreira (2002) concluded that the faster the water loss rate, the higher the oil adhesion at the chips surface and then the higher oil absorption. In addition, as the percentage of free water is depleted in the product, less oil is absorbed. The pressurization step plays an important role in reducing the oil absorption during vacuum frying. It can increase or decrease oil absorption in the product depending on the amount of surface oil and free water presented in the product.

Troncoso et al. (2009) found that vacuum frying (5.37 kPa, 120 °C) increased significantly oil content of potato chips as compared to atmospheric frying (140 °C). They concluded that in vacuum frying the heat and mass transfer rates are higher than in atmospheric frying due to the decrease in the boiling point of water at vacuum pressure (5.37 kPa and T_boil = 34 °C). The pressurization process rapidly increases the pressure at the pores, causing the oil adhered at the chip’s surface to penetrate in the food (generating a “sponge effect”), until the pressure at the pores equals the atmospheric pressure.

Shyu and Hwang (2001) produced good quality (texture, color, and flavor) apple chips by osmotically dehydrating (in 50% glucose solution) the product and then freezing it (~30 °C) prior to vacuum frying (98.66 kPa). To reduce the final oil content of the product (34% w.b. fried at 110 °C for 5 min), they used a centrifuge (at 350 rpm for 30 min) after frying, before depressurizing the fryer. Using the same treatment, Shyu et al. (2005) produced carrot chips with 12.3% w.b. oil content.

Many vacuum frying units are equipped with centrifuges for de-oiling the product after frying. The centrifuges are installed in a special vacuum dome attached to the vacuum fryer (BMV, Woerden, The Netherlands, 2008).

The objective of this study was to establish the effect of de-oiling and frying temperature on potato chips quality and oil absorption. The experimental data was fitted using non-linear regressions to determine predicted equations for moisture content, oil content, porosity, and color.

2. Materials and methods

2.1. Raw material

Potatoes, variety Atlantic, were provided by the Texas A&M University Potato Variety Development Program.

2.2. Sample preparation

About 30 g of potatoes were peeled and then sliced to 1.6 mm thickness and 5 cm diameter (Mitutoyo Thickness Gage, Japan) using a Mandolin Slicer (Matfer model 2000, France).

2.3. Frying experiments

A detailed description of the process is described elsewhere (Garayo and Moreira, 2002). Fig. 1 illustrates a schematic of the vacuum system. The vacuum vessel was set to the target temperature and allowed to operate for 1 h before frying started. Fresh canola oil was used in all experiments. The volume of oil used was 8 L.

The process (operating at P < 1.33 kPa) consisted of loading the products into the fryer basket (about 30 g per batch), closing the lid, and then depressurizing the vessel. When the pressure in the vessel achieved vacuum, the basket was submerged into the hot oil. Once the products were fried, the basket was raised, the vessel pressurized up to atmospheric pressure, and then the samples were stored in polyethylene bags inside of desiccators for further analysis. The temperatures used to fry the potatoes were 120, 130, and 140 °C. A centrifuging step (750 rpm (63 g units) for 40 s) before pressurizing the vessel after frying was added and its effect on final oil content (FOC) and product quality evaluated using standard methods.

The centrifuge system consists of a motor attached to the basket shaft, which rotates at 770 rpm (63 g units). The potatoes were centrifuged for about 40 s (optimum time according to preliminary results) before the fryer was pressurized.

3. Product quality attributes

3.1. Oil content

The Soxtec System HT extraction unit (Pertorp, Inc., Silver Spring, MD) was used to determine the oil content of the samples using petroleum ether as solvent (AACC, 1986). The oil content was divided into three types: (1) total oil content (TOC) defined as the oil content of the product after frying without any de-oiling process; (2) internal oil content (IOC), i.e., the oil content of the chips after the de-oiling process; and the (3) surface oil content (SOC) was defined as the TOC minus the IOC. All measurements were made at least in triplicate.
3.2. Moisture content

Moisture content of fried samples was measured using a vacuum oven (Squared Lab Line Instruments, Melrose Park, IL, USA), according to AOAC method 930.04 (1990). Measurements were made at least in triplicate.

3.3. Color

A Labscan XE colorimeter (Hunter Lab, Inc., Reston, VA, USA) with the Universal v.3.73 software was used to evaluate the fried products color using the CIELAB system. The measuring aperture diameter was 36 mm, the illuminant was the D65, and 10° for the observer. The colorimeter was calibrated using standard white and black tiles. Ten randomly samples were evaluated and five readings were recorded as an average reading. Mean values of the coordinates $L^*$ (lightness–darkness), $a^*$ (redness–greenness), and $b^*$ (yellowness–blueness) were used to determine the color of the produce through reflectance mode.

3.4. Texture

We measured the texture of the potato slices at room temperature (21 °C) using a Texture Analyzer (TA.XT2i, Texture Technologies Corporation, Scardale, NY, USA) equipped with a TA-101 Crisp chip/cracker fixture with $1/4$” rounded end probe. One slice of potato for each treatment (frying time, temperature, and with or without centrifugation) was placed on the sample holder (hollow cylinder) and the probe was forced through the slice (rupture test mode). The probe was set at an initial height of 30 mm from the bottom of the sample holder to move at 0.1 mm/s. Once the probe touched the sample, it was set to travel to a distance of 4.0 mm. The Texture Expert software program recorded the maximum force (N) required to break the samples. Ten measurements were performed for each treatment.

3.5. Solid density

To obtain the solid volume of potato chips, the pre-weighed samples were ground using a coffee grinder (Braun, Model KSM2) and placed in a compressed helium gas multi-pycnometer (Quantachrome & Trade, NY, USA). Solid density, $\rho_s$ (kg/m$^3$), was determined by dividing the weight of the sample by its solid volume. The test was performed in triplicate.

3.6. Bulk density

The bulk volume was measured using the liquid displacement technique with toluene (Wang and Brennan, 1995; Lozano et al., 1983). Bulk density, $\rho_b$ (kg/m$^3$), was then determined by dividing the weight of the chip by its bulk volume. The test was performed in triplicate.

3.7. Porosity

Porosity, $\phi$, was calculated as:

$$\phi = 1 - \frac{\rho_b}{\rho_s}$$

(1)

3.8. Degree of shrinkage

The diameter of the samples was measured using a Mitutoyo Thickness Gage. About 20 readings were made for five samples of each treatment. Degree of diameter shrinkage ($S_i$) was calculated by:

$$S_i = \left(\frac{d_0 - d(t)}{d_0}\right) \times 100$$

(2)

where $d_0$ is the original dimension of raw sample (mm) and $d(t)$ is the dimension of sample with frying time (mm).

4. Statistical analysis

Determination of non-linear and linear regression parameters was conducted using the Marquard Compromise iteration method in the graphics software package PlotIt (version 3.2, 1999). Differences among treatments were detected with the SPSS software (version 12.0.1 for Windows, 2003) using Duncan’s multiple range tests. Statistical significance was expressed at the $P < 0.05$ level.
5. Results

5.1. Oil content

Fig. 2 shows the oil distribution in the potato chips fried at 120 °C at 1.33 kPa for 360 s. The oil content (TOC) of the non-centrifuged chips increased to about 0.77 g/g solid (0.43 g/g product) by the end of frying compared to 0.11 g/g solid (0.97 g/g product) for the centrifuged samples (IOC). Most of the oil was absorbed in the first 180 s of frying. By the end of frying, only 14% of the total oil content (TOC) was internal oil (IOC) while 86% was surface oil (SOC). About 34% of the IOC and only 0.7% of the SOC was absorbed during the first 20 s of frying. These results clearly show the effect of using the de-oiling process to remove the oil content from the surface of the samples. About 86% of the oil content in the chips can be easily removed by the centrifuge process without affecting the other quality attributes of the product, specifically breakage susceptibility. Some preliminary results (not shown) indicated that centrifuging time can affect the oil removal to a maximum value of 80–90% of the TOC.

The kinetics of oil distribution in potato chips was modeled by using a special case of the logistic kinetic model (Chen and Ramaswamy, 2002) that accurately describes product quality attributes that increase exponentially and eventually level-off:

\[ C(t) = A_0 + \frac{A}{1 + \exp(-k(t - t_0))} \]  

where \( C \) is the quality variable (in this case the oil content) at time \( t \) (s), \( A_0 \) is the quality attribute before frying (= 0 in this case), \( A \) is a constant value related to the equilibrium quality attribute, \( k \) is the rate constant (1/s), and \( t_0 \) (s) is the time constant value when the quality attribute increases to half of \( A \) value.

Table 1 shows the values of the parameters in Eq. (3) for different frying conditions. Fig. 2 shows the experimental and fitted values for the oil absorption using this model. It can be seen from Table 1 that the values for \( A \) (equilibrium oil content) decreased with oil distribution. Also, the \( t_0 \) value decreased for the IOC curve, indicating that oil content will reach half of its maximum value earlier (in 36 s) in the frying process. The internal oil absorption rate constant \( k \) was higher compared to the TOC and SOC. This results show that the IOC reaches equilibrium earlier (~100 s) in the process. Also, most of the oil stays at the surface of the chips, which is easily removable by a de-oiling process as shown later in this study.

Table 1

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>TOC [g/g solid]</th>
<th>IOC [s]</th>
<th>SOC [g/g product]</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>120°C</td>
<td>0.82</td>
<td>99</td>
<td>0.033</td>
<td>0.954</td>
</tr>
<tr>
<td>120°C</td>
<td>0.11</td>
<td>36</td>
<td>0.070</td>
<td>0.895</td>
</tr>
<tr>
<td>120°C</td>
<td>0.068</td>
<td>100</td>
<td>0.084</td>
<td>0.994</td>
</tr>
</tbody>
</table>

Not centrifuged; b centrifuged. Fried for 360 s at 1.33 kPa and using the de-oiling process at 750 rpm for 40 s before the vessel was pressurized. Moisture tests were run in triplicates. TOC = total oil content (potato slices fried without de-oiling); IOC = internal oil content (slices fried and de-oiled); SOC = surface oil content (TOC – IOC).

5.2. Oil temperature

The final oil content of potato chips was significantly different (\( P < 0.05 \)) for the samples fried under vacuum conditions for 360 s, de-oiled at 750 rpm (63 g units) for 40 s, and different oil temperatures (Fig. 3). However, no significant differences were observed when comparing the oil content on the samples fried until the final moisture content values were similar, i.e., around 0.014 g/g product (frying time varied from 360, 240, and 180 s for \( T = 120, 130, \) and 140 °C, respectively), as expected (Moreira et al., 1999). In general, oil temperature does not affect the final oil content; oil content is related to final moisture remaining in the chips after frying.

At higher temperatures, the chip’s oil content reached its maximum value early in the frying process, then decreased as frying time increased, i.e., the oil absorption rate increased as temperature increased. For instance, after 120 s at 140 °C, the oil content was about 0.11 g/g product; the content went down and remained fairly constant (0.07 g/g product) to the end of frying. The highest oil content during vacuum frying at 140 °C coincides with the period at which water evaporated from the potato slices at the fastest rate at this temperature (Fig. 4). So, the higher the oil temperature, the higher the oil uptake by the potato chips during the first 120 s of frying, as was also observed by Granda (2005) and Garayo and Moreira (2002). Fig. 3 shows that the behavior of oil content for chips fried at 130–140 °C is different from those fried at the lower temperature (120 °C). This difference occurs during the pressurization period, which can decrease or increase oil absorption depending on the amount of free water and surface oil in the product. When the chips fried at 130–140 °C are removed from the oil at the beginning of frying (less than 120 s) the water vapor in the pores condenses, and the pressure difference (\( \Delta P = P_{ambient} - P_{pore} \)) drives the oil into the product. The amount of oil absorbed during pressurization will increase until a critical level. At this point, oil
absorption during the pressurization process decreases, since $\Delta P$ is negligible. So, when frying under vacuum (1.33 kPa) at 130–140 °C, the highest oil content is reached when free water is still available to the product, then it decreases until the equilibrium moisture content is reached. At 120 °C, the higher free water content makes it difficult for the oil to enter the pore spaces, so the peak observed at 130–140 °C was not seen at the lower temperature at 120 s frying. Thus, the higher the temperature, the higher the oil content of the chips during the initial frying period, when free water is still available in the product (Garayo and Moreira, 2002; Granda, 2005).

In this case, the rate of oil content change with temperature was modeled using a fractional conversion kinetic model (Chen and Ramaswamy, 2002):

$$OR = \frac{OC(t) - OC_e}{OC_e - OC_0} = A \exp(-kt)$$

(4)

where $OR$ is the oil ratio, $OC_e$ is the equilibrium oil content, $OC_0$ is the initial oil content, $A$ and $k$ are the regression coefficients, and $t$ = frying time.

During vacuum frying at 130 and 140 °C, two regions were defined for the kinetic model: from 0 to 120 s, and from 120 to 360 s, since these two regions showed different behavior. Table 2 shows the values of the kinetic parameters. Table 2 shows the values of the parameters in Eq. (4). As expected, the higher the temperature the higher the oil absorption rate.

5.2. Moisture loss

The de-oiling process had not significant effect ($P < 0.05$) on the final moisture content or the moisture loss behavior of the potato chips. Fig. 4 shows the moisture loss of potato slices fried under vacuum and oil temperatures. These curves exhibit typical drying profiles for food products.

The diffusion coefficient is a measure of molecular mobility. Hence, a higher moisture diffusion coefficient in potato slices means a faster drying rate. The diffusion coefficient of the potato slices or chips fried at different temperatures under vacuum and traditional frying was calculated using the method proposed by Brooker et al. (1992). The moisture diffusion equation for a flat plate can be described by:

$$MC_{db} = (M_i - M_e) \left( \frac{8}{\pi^2} \right) \exp \left( -\frac{\pi^2 D_e t}{4a^2} \right) + M_e$$

(5)

where $MC_{db}$ is the moisture content in (g/g solid), $M_i$ is the initial moisture content (g/g solid), $M_e$ is the equilibrium moisture content (g/g solid), $t$ is the frying time, and $a$ is half of the potato slice. The values of $D_e$ (effective diffusion coefficient) were obtained by using non-linear regression to fit the experimental drying rate curve (Table 3).

The influence of the frying oil temperature on the diffusion coefficient during vacuum frying was modeled using an Arrhenius-type equation:

$$D_e(T) = A \exp \left( \frac{-E_a}{RT} \right)$$

(6)

where $A$ is the pre-exponential factor (1/s), $E_a$ is the activation energy (J/mol), $T$ is the absolute temperature (K), and $R$ is the universal gas constant (8.314 J/molK).

Eq. (6) can be linearized as:

$$\ln D_e = \ln A + \frac{E_a}{RT}$$

(7)

The following relationships were found for the centrifuged chips:

$$\ln D_e = -2.7122 - 4672.16 \frac{1}{T}, \quad R^2 = 0.937$$

(8)

The pre-exponential factors ($A$) for potato chips fried under vacuum frying was $6.64 \times 10^{-3}$ (1/s). The activation energies ($E_a$) was $38,844.34$ J/mol (for $120 °C \leq T \leq 140 °C$), for the centrifuged samples.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>$D_e$ [m²/s]</th>
<th>$M_e$ [g/g solid]</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.2314</td>
<td>5.0868 x 10⁻⁷</td>
<td>0.0050</td>
</tr>
<tr>
<td>130&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.2511</td>
<td>4.3734 x 10⁻⁷</td>
<td>0.0150</td>
</tr>
<tr>
<td>140&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3.2314</td>
<td>6.6743 x 10⁻⁷</td>
<td>0.0150</td>
</tr>
<tr>
<td>140&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3.2314</td>
<td>7.7612 x 10⁻⁷</td>
<td>0.0150</td>
</tr>
</tbody>
</table>

<sup>a</sup> Not centrifuged; <sup>b</sup>Centrifuged. Fried for 360 s at 1.33 kPa and using the de-oiling process at 750 rpm for 40 s before the vessel was pressurized. Moisture tests were run in triplicates. Thickness of the potato slices for $D_e$ calculations was $1.6 \times 10^{-3}$ m, so $a$ in Eqn (5) is equal to $0.8 \times 10^{-3}$ m.

Table 2

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>$OC_0$ [g/g product]</th>
<th>$OC_e$ [g/g product]</th>
<th>$A$</th>
<th>$k$ [1/s]</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.0104</td>
<td>0.11</td>
<td>1.243</td>
<td>0.0096</td>
<td>0.976</td>
</tr>
<tr>
<td>130</td>
<td>0.0211</td>
<td>0.14</td>
<td>1.450</td>
<td>0.0144</td>
<td>0.842</td>
</tr>
<tr>
<td>140</td>
<td>0.0295</td>
<td>0.12</td>
<td>1.992</td>
<td>0.0099</td>
<td>0.720</td>
</tr>
<tr>
<td>140</td>
<td>0.12</td>
<td>0.065</td>
<td>1.728</td>
<td>0.0066</td>
<td>0.917</td>
</tr>
</tbody>
</table>

<sup>a</sup> Initial oil content.  
<sup>b</sup> Equilibrium oil content (final oil content).  
<sup>c</sup> Units in g/100 g of whole product.
5.3. Color changes

The \( L^* \)-value (lightness) and \( a^* \)-value (green–red chromaticity) do not follow a clear trend for potato slices samples fried under vacuum (Granda, 2005) and the same behavior was observed in this study. The most obvious differences in color are found in the \( b^* \)-values (blue–yellow chromaticity). It was found that the \( b^* \)-values for the centrifuged chips were not significantly higher \((P < 0.05)\) than those non-centrifuged at all times (not showing).

It was noticed that as frying time and temperature increased, the \( b^* \)-value also increased (Fig. 5). However, it was found that the \( b^* \)-values were significantly lower \((P < 0.05)\) for the samples fried at 120 °C than for those fried at 130 or 140 °C. Higher temperatures produced darker chips than lower temperature, but there were not significant differences in the chips color when fried at 130–140 °C.

Kinetics of color changes in centrifuged potato chips was also modeled by using Eq. (3). Table 4 shows the values of the parameters for different frying temperatures. Fig. 5 shows the experimental and fitted values for \( b^* \)-values changes using this model. It can be seen that the values for \( A \) (equilibrium color value) increased with increasing temperature. This was expected since higher temperatures produce higher levels \( b^* \)-values due to increased Maillard reaction. Also, as temperature increased from 120–130 °C, \( t_o \) increased, i.e., at higher temperatures the \( b^* \)-value will reach half of its maximum value later in the frying process. Little changes were observed in color from chips fried from 130–140 °C. As temperature increased at the same range, the color change rate constant \( k \) increased as expected, since higher temperatures enhance the rate of color changes.

By comparing the centrifuged and non-centrifuged samples fried at 120 °C, all the parameter values were a little higher for the non-centrifuged chips (Table 4).

5.4. Porosity

Fig. 6 shows the effect of the de-oiling process on the porosity of potato chips fried at 120 °C for 360 s. The samples that were centrifuged showed, as expected, higher porosity than the non-centrifuged ones because of their lower oil content (Fig. 2). The de-oiling process helps to remove most of the absorbed oil from the chip’s surface thus increasing the pore space.

Table 5 shows the values of bulk density, solid density, and porosity for all the samples after 360 s of frying in function of temperature. The non-centrifuged samples had higher final bulk density and lower porosity than the centrifuged ones at 120 °C. Bulk density decreased slightly by end of frying with temperature. However, porosity values were not significant different \((P < 0.05)\) with temperature for the de-oiled samples.

Eq. (4) (with oil content replaced by porosity) was used to predict the experimental data for porosity and Table 6 shows the values of the parameters for different frying temperatures. Fig. 7 shows the effect of the de-oiling process on the porosity of potato chips (Atlantic variety) porosity changes during frying at 120 °C.

Table 4
Regression coefficients of the time dependent logistic model for color changes in potato chips (Atlantic variety) during vacuum frying (1.33 kPa).

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>( A ) [-]</th>
<th>( t_o ) [s]</th>
<th>( k ) [1/s]</th>
<th>( A_k ) [-]</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>120°</td>
<td>21</td>
<td>113</td>
<td>0.012</td>
<td>2.0</td>
<td>0.982</td>
</tr>
<tr>
<td>120°</td>
<td>20</td>
<td>80</td>
<td>0.010</td>
<td>2.0</td>
<td>0.993</td>
</tr>
<tr>
<td>130°</td>
<td>30</td>
<td>115</td>
<td>0.015</td>
<td>0.9</td>
<td>0.976</td>
</tr>
<tr>
<td>140°</td>
<td>32</td>
<td>100</td>
<td>0.014</td>
<td>0.5</td>
<td>0.976</td>
</tr>
</tbody>
</table>

*Not centrifuged; \(^b\) centrifuged. Fried for 360 s at 1.33 kPa and \(^b\) using the de-oiling process at 750 rpm for 40 s before the vessel was pressurized. Color tests were run in triplicates.

Table 5
Bulk density, solid density, and porosity of potato chips (Atlantic variety) fried under vacuum (1.33 kPa) at different temperatures.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>Solid density [kg/m³]</th>
<th>Bulk density [kg/m³]</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>120°</td>
<td>803 ± 40</td>
<td>0.36 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>120°</td>
<td>564 ± 28</td>
<td>0.61 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>130°</td>
<td>575 ± 29</td>
<td>0.60 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>140°</td>
<td>488 ± 24</td>
<td>0.68 ± 0.03</td>
<td></td>
</tr>
</tbody>
</table>

*Not centrifuged; \(^b\) centrifuged. Fried for 360 s at 1.33 kPa and \(^b\) using the de-oiling process at 750 rpm for 40 s before the vessel was pressurized. All the property tests were run in triplicates.

Table 6
Porosity rate constant \((k)\) values for potato chips (Atlantic variety) fried under vacuum frying (1.33 kPa) at different temperatures and using the de-oiling process at 750 rpm for 40 s.

<table>
<thead>
<tr>
<th>Temperature [°C]</th>
<th>( \text{Por}_{\text{a}} % )</th>
<th>( \text{Por}_{\text{b}} % )</th>
<th>( A )</th>
<th>( k ) [1/s]</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>0.008</td>
<td>0.065</td>
<td>1.381</td>
<td>0.01006</td>
<td>0.940</td>
</tr>
<tr>
<td>130</td>
<td>0.009</td>
<td>0.065</td>
<td>1.546</td>
<td>0.0156</td>
<td>0.859</td>
</tr>
<tr>
<td>140</td>
<td>0.008</td>
<td>0.075</td>
<td>1.604</td>
<td>0.0181</td>
<td>0.847</td>
</tr>
</tbody>
</table>

* Initial porosity.
\(^b\) Equilibrium porosity (final porosity).
shows the experimental and fitted values for porosity changes with
temperatures using this model. The porosity of the potato chips in-
creased slightly with temperature for the de-oiled samples. The
behavior of porosity rate looks similar to the oil absorption rate
during frying (Fig. 2), as expected.

5.5. Diameter shrinkage

No significant differences ($P < 0.05$) in diameter were observed
between the centrifuged and non-centrifuged treatments during
the entire process (not showing).

Diameter shrinkage increased with time and temperature of
frying for the de-oiled samples (Fig. 8), however, no significant dif-
cferences ($P < 0.05$) were absorbed among the samples. It seems
that diameter shrinkage tends to level-off as frying time increases.
The higher the temperature the faster the product reaches its final
diameter.

5.6. Texture

The de-oiling process has no significant effect ($P < 0.05$) on the
product texture (not showing). The frying time and oil temperature
(Fig. 9) also did not affect the texture of the de-oiled samples at the

6. Conclusions

The de-oiling process is an imperative step in vacuum frying of
vegetable snacks such as potato chips. Because of the higher heat
and mass transfer rates in the process, oil absorption increases at
the product’s surface. This oil must therefore be removed under
vacuum after the product is fried. The process evaluated in this
study can de-oil as much as 90% of the surface oil content of potato
chip’s surface prior to frying, before the vessel is pressurized to the
atmospheric conditions. Removal of the surface oil after the fryer is
pressurized will not be as effective because of higher $\Delta P$ and $\Delta T$
between the two ambient conditions will drive the surface oil
within the product before it can be washed out from the surface.

The other product quality attributes, such as color, texture,
moisture, and diameter shrinkage are not affected by the de-oiling
process. Porosity, on the other hand, is directly related to the oil
content of the product, i.e., higher oil content results in lower
porosity.

The effect of oil temperature (for the de-oiled samples) and fry-
ing time on the product quality attributes showed that darker
chips are produced at higher frying temperatures; low temperature
can produce samples harder to break; the higher the temperature
the lower the final oil content and hence, the higher the porosity.
However, by the end of frying, porosity values were not signifi-
cantly different with temperature. Diameter shrinkage was inde-
pendent of temperature.

Experimental data for color and oil distribution with tempera-
ture can be predicted using a special case of the logistic model.
The kinetics of oil distribution and porosity with temperature
can be described using the fractional conversion exponential mod-
el. The moisture loss diffusion coefficient increases with frying
temperature. Diameter shrinkage and texture experimental data
showed large variability with temperature and time and hence
did not show a clear trend in this study. New methods for measur-
ing texture and diameter for vacuum fried products need to be
developed to reduce the problems with large standard deviations
in the measurements.

Acknowledgements

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ety Development Program for providing the potatoes for this and
other investigations, especially to Dr. Creighton Miller and Doug Scheuring.

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