Mini Review

Vacuum frying foods: products, process and optimization

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Abstract

Vacuum frying is a reasonably new technology which uses lower pressure and temperature rather than atmospheric deep-fat frying to improve the quality attributes of food products. This work reviewed published research papers on vacuum fried foods from 2012 to the present, including some papers not covered by two recent reviews. The review covered the vacuum frying system, the vacuum frying process, product, process and optimization, oil uptake, changes in the oil during vacuum frying, and packaging and shelf life of vacuum fried foods. The vacuum fried products processed comprised of fruits, vegetables, fish and wheat-based snacks. Some of the studies recommended optimized conditions for a number of products including apple, apricot, carrot, grass carp, gold and green kiwifruits, mushrooms, potato and shallots. Generally, the higher the frying temperature the shorter the frying time. However, there was a wide range of vacuum pressures used ranging from 1.33 to 90 kPa with more than half of the processes carried out at lower than 10 kPa. Many of the products were not centrifuged after vacuum frying so would be expected to have higher oil content. For the vacuum fried products that were centrifuged, these were either carried out within the frying chamber or outside it, using speeds of 140-1000 rpm for 2-10 minutes.

Introduction

Vacuum frying is a frying process that is carried out at pressures well below atmospheric level. It has been used for different foods, but mostly fruits and vegetables. The latest reports include apple, apricot, banana, jackfruit, green and gold kiwifruits, carrot, mushroom, potato, shallot, sweet potato and purple yam. Vacuum frying offers an alternative way to improve the quality of fried fruit and vegetables other than by atmospheric frying (Dueik and Bouchon, 2011a). The main factors that influence fried products are the frying time-temperature combination of the cooking process; the correct combination of which is necessary to produce a food product with acceptable physical attributes (Andres-Bello *et al.*, 2011). Dueik and Bouchon (2011a) showed that vacuum frying significantly lowered the final oil content in comparison to atmospheric fried vegetables and it also slowed the rancidity of the oil. Most of the benefits of vacuum frying from the low temperatures used and the minimal exposure to oxygen, which reduces the adverse effects on the oil quality (Shyu *et al.*, 1998), preserves the natural colour and flavour (Shyu and Hwang, 2001), decreases the acrylamide content (Granda *et al.*, 2004) and preserves nutritional compounds, such as vitamins and minerals (Da Silva and Moreira, 2008). Vacuum frying is a good option to achieve high quality dried products with better colours and flavours due to the reduced oxidation, lower frying temperatures and much shorter processing times compared with other techniques (Da Silva and Moreira, 2008).

Vacuum fried products are prepared using fresh fruits and vegetables that are peeled and cut into small pieces. The operating pressure used is usually lower than 7 kPa which produces a good reduction in the boiling point of water and allows the frying temperature to be lower than 90°C (Dueik and Bouchon, 2011a).

Although there have been previous reviews on the vacuum frying of foods (Andres-Bello *et al.*, 2011; Dueik and Bouchon, 2011b), there are also newly published papers on this subject (Diamante *et al.*, 2012a; Diamante *et al.* 2012b; Diamante *et al.*, 2012c; Dueik *et al.*, 2012; Fang and Bao, 2012; Mir-Bel *et al.*, 2012; Pandey and Moreira, 2012; Presswood, 2012; Warning *et al.*, 2012; Yang *et al.*, 2012; Diamante *et al.*, 2013; Haizam *et al.*, 2013; Ravli *et al.*, 2013; Sobukola *et al.*, 2013; Chen *et al.*, 2014; Crosa *et al.*, 2014) and other papers not covered by the two previous reviews (Apintanapong *et al.*, 2007; Fan *et al.*, 2007; Therdthai *et al.*, 2007; Yamsaengsung *et al.*, 2008; Diamante, 2009; Diamante *et al.*, 2011; Fang *et al.*, 2011; Maadyrad *et al.*, 2011; Sothornvit, 2011; Tarzi *et al.*, 2011;

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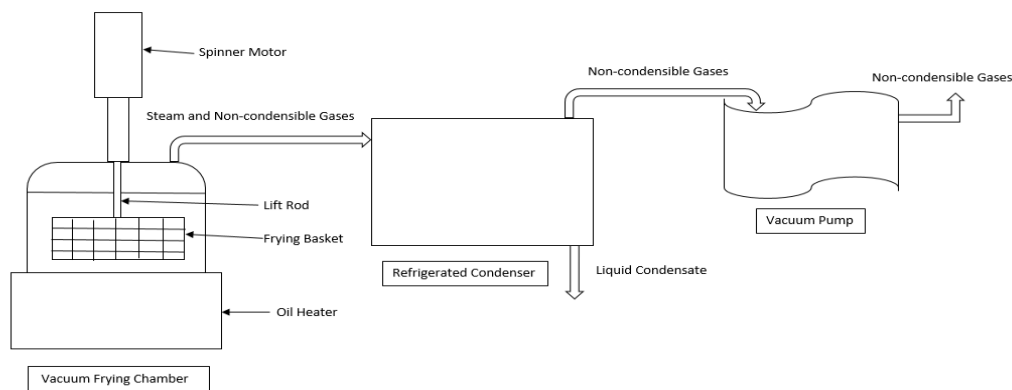Email: Lemuel.Diamante@lincoln.ac.nz

Figure 1. A sample vacuum frying system

Yamsaengsung *et al*., 2011). This review will cover the product, process and optimization of vacuum frying of foods.

Vacuum frying system

A vacuum frying system consists of three components, namely: a) a vacuum frying chamber; b) a refrigerated condenser; and c) a vacuum pump (Figure 1). The vacuum frying chamber is an airtight vessel provided with an oil heater and a frying basket. The frying basket is raised and lowered into the heated oil by a lift rod. The lift rod is usually connected to a spinner motor that is used for centrifuging the product after frying to get rid of surface oil. The refrigerated condenser is provided to trap the evolved steam during frying by condensing it on a cold surface. The use of a refrigerated condenser is recommended for better efficiency compared with water-cooled condensers. The vacuum pump provides the required low pressures for the process and get rid of non-condensable gases.

Andres-Bello *et al*. (2011) discussed the vacuum frying system or equipment in their review paper. They mentioned that there were three kinds of equipment in terms of size: laboratory, pilot and industrial and in terms of processing requirements: batch and continuous processes. They showed and discussed three examples of vacuum frying systems.

A vacuum frying system used in processing bananas was reported by Yamsaengsung *et al*. (2011) that consisted of a gas-heated vacuum frying chamber, a water-cooled condenser and a liquid ring vacuum pump. The fried product can be centrifuged at 450 rpm within the frying chamber. Sothornvit (2011) on the other hand, reported on a different configuration of vacuum frying system used in processing also with bananas consisting of a vacuum frying chamber provided with heated oil from another chamber, a water-cooled condenser using a cooling tower and an oil-sealed vacuum pump. The fried product can be centrifuged at either 140 or 280 rpm within the frying chamber.

Diamante (2009) presented a picture of a vacuum frying system used in the preparation of jackfruit chips. The vacuum frying system consisted of a vacuum frying chamber, a water-cooled condenser using a cooling tower and liquid ring vacuum pump. After vacuum frying the jackfruit chips were taken out of the chamber and centrifuged at atmospheric pressure in a separate machine. Diamante *et al*. (2011) also presented the vacuum fryer used in processing gold kiwifruit slices that consisted of a steam-heated vacuum frying chamber, a water-cooled condenser and an oil-sealed vacuum pump. The fried product was also centrifuged at atmospheric pressure using another machine.

An analysis of a batch vacuum frying system for potato chips was reported by Pandey and Moreira (2012). They used a vacuum frying system consisting of an electric-heated vacuum frying chamber, a refrigerated condenser and an oil-sealed vacuum pump. The fried product can be centrifuged within the drying chamber at speeds up to 750 rpm.

The vacuum frying systems available varied in designs but still consist of the same basic parts, namely: a) a vacuum frying chamber; b) a condenser; and c) a vacuum pump. The method of heating the oil in the frying chamber can be gas, steam or electricity. The condenser used water or refrigeration to condense the steam evolved during frying. The vacuum pump used can be a liquid ring vacuum pump or an oil-sealed vacuum pump. In addition, some vacuum frying systems incorporate a means of centrifuging the fried samples within the frying chamber.

Vacuum frying process

The vacuum frying process required the heating of oil to the required temperature. Then the sample to be processed was placed in the basket inside the frying chamber but suspended above the hot oil. The pressure inside the vacuum frying chamber was reduced to the required pressure. The sample was

then lowered into the hot oil for the required duration and then the basket was raised above the oil and then centrifuged within the chamber for the required speed and time. The fried product can also be taken out of the chamber and centrifuged using a separate machine or stood in the frying chamber to drain the surface oil. The product was then placed on absorbent paper, cooled and packed in an aluminium laminate bag with or without nitrogen flushing.

The principles of vacuum frying were discussed in detail in the review paper of Dueik and Bouchon (2011a). They stated that the operating pressures should preferably be lower than 7 kPa, which caused a great reduction in the boiling point of water, allowing frying to be carried out at temperatures even lower than 90°C. It was important to note that the temperature should not be too low otherwise the required structural changes may not take place. The batch equipment consisted of a stainless steel vessel covered with a hermetic lid connected to a vacuum system, which was adequately separated from the vessel by means of a condenser when an oil vacuum pump was used.

Andres-Bello *et al*. (2011) discussed in their review two important aspects of the vacuum frying process, namely, oil uptake and moisture loss. They showed and discussed various empirical and non-empirical mathematical models to evaluate oil intake during vacuum frying. They also presented and explained empirical and non-empirical models to evaluate moisture loss during vacuum frying.

A simulation of the heat and mass transfer processes during vacuum frying of potato chips was reported by Yamsaengsung *et al*. (2008). The simulation of the heat transfer process included the convection of heat from the oil surface to the product, the conduction of heat into the product, and the loss of heat when using the heat source term to represent evaporation. The mass transfer process was divided into two periods: a) water loss and b) oil absorption. From the simulation, a good agreement between the experimental data and the predicted values was obtained. The heat transfer model validated, a rapid increase in temperature of the product toward the boiling point of water (at the associated pressure) followed by a steady increase toward the temperature of the oil. Furthermore, by separating the rate of moisture loss into two parts to represent the constant rate and falling rate periods of drying, the model was able to predict an initial period of rapid loss followed by a decreasing rate of loss.

Pandey and Moreira (2012) carried out an analysis of a batch vacuum frying system for potato chips. Potato slices were fried at 120 and 140°C oil

temperatures and 1.33 kPa pressure. The temperatures of the fryer headspace and the centre of the potato slices were monitored during frying. The convective heat transfer coefficients *(h)* were calculated using the lumped capacity method for varying frying loads. They found that the heated oil *h* values were 217 ± 13 W.m^{-2}. K^{-1} (120°C) and 258 ± 37 W.m^{-2}.K^{-1} (140°C). The *h* values increased up to 3.6 times during the boiling period.

The influence of temperature on the heat transfer coefficient during moderate vacuum deep-fat frying of potato cylinders and "churros" was studied by Mir-Bel *et al*. (2012). The vacuum frying conditions used were oil temperatures of 100-140°C and moderate vacuum of 19.5-25.9 kPa. The *h* changes considerably, reaching a maximum of between 700-1600 W.m^{-2}.K^{-1} for an oil temperature of 140°C and a thermal gradient of 40°C. To quantify the effect of oil temperature, pressure and size of the product on *h*, a parameter called "bubbling efficiency" (BE), was defined. BE related the bubble departure radius to the area/volume ratio of the product. An equation (the derivative of the Gompertz function) was proposed to estimate the mean *h* for each frying condition as a function of BE. The relation of h and BE showed a maximum corresponding to an optimal bubbling pattern.

Warning *et al*. (2012) proposed a porous media based model for deep-fat vacuum frying of potato chips. They developed a multiphase porous media model describing heat, mass and momentum transfer within a potato chip during vacuum frying following the work of Halder *et al*. (2007). The temperature, moisture, pressure, acrylamide content and oil content inside a potato chip during vacuum frying were obtained using the proposed model. The predictions compared well with experimental data from various researchers. The average simulated temperature rapidly increased and reached a plateau before approaching the oil temperature, as in the experimental results. The moisture content of the simulated and experimental results were comparable when using a non-equilibrium evaporation rate for the simulation. Regardless of the frying pressure, the core experienced pressures approximately 40 kPa higher than at the surface. The oil content was qualitatively similar to the experimental results and the acrylamide concentration matched the experimental results when using the potato temperature rather than the oil temperature.

The studies showed that there was a rapid increase in temperature of the potato product towards the boiling point of water (at the associated pressure) followed by a steady increase towards the temperature

Table 1. Vacuum frying conditions for different products

Product	Temp. (°C)	Time (mins.)	Pressure (kPa)	Optimised	Centrifuged	Reference
Apple	98	4.5	6.48	yes	no, product stood for 3 minutes	Dueik and Bouchon, 2011b
Apricot	100	72.5	2.3	yes	no, product stood for 4 minutes	Diamante *et al.*, 2012b; 2012c
Banana	90	90	9.33	no	not mentioned	Apintanapong *et al.*, 2007
	89	90	2.66	no	140 or 280 rpm for 5 minutes	Sothornvit, 2011
	110	20	8.0	no	not mentioned	Yamsaengsung *et al.*, 2011
Carrot	98	5	6.48	yes	no, product stood for 3 minutes	Dueik and Bouchon, 2011b
Chinese						
Purple Yam	100	15	90	no	450 rpm for 5 minutes	Fang *et al.*, 2011
Grass Carp	130	13	60	yes	not mentioned	Zhang and Bao, 2012
	100-110	15	80	yes	300 rpm for 2 minutes	Chen *et al.*, 20014
Gold Kiwifruit	80	50	2.3	no	no, product stood for 4 minutes	Diamante *et al.*, 2011
	72-76	35-65	2.3	yes	no, product stood for 4 minutes	Diamante *et al.*, 2012a; 2013
Green Kiwifruit	105	8	6.2	yes	750 rpm for 4 minutes	Maadyrad *et al.*, 2011
Jackfruit	90	135	6.76	no	not mentioned	Diamante, 2009
Mushrooms	90	12.5	4.25	yes	400 rpm for 10 minutes	Tarzi *et al.*, 2011
Potato	98	6.5	6.48	yes	no, product stood for 3 minutes	Dueik and Bouchon, 2011b
Shallot	108	13	27.86	yes	1000 rpm for 3 minutes	Therdthai *et al.,* 2007
Sweet Potato	90	30	20	no	400 rpm, time not mentioned	Yang *et al.*, 2012
	130	2.33	1.33	no	not mentioned	Ravli *et al.*, 2013
Wheat-based						
Snack	141	4	33.21	no	no, product stood for 3 minutes	Sobukola *et al.*, 2013

of the oil during vacuum frying. The rate of moisture loss of the potato product during vacuum frying can be divided into two parts: the constant rate and the falling rate periods of drying. The convective heat transfer coefficients during vacuum frying of potato at low pressure were much lower than during vacuum frying at moderate pressures. The average temperature of the potato during vacuum frying rapidly increased then reached a plateau before approaching the oil temperature. Regardless of the frying pressure, the potato core experienced pressures of approximately 40 kPa higher than at the surface.

Product, process and optimization

A number of products have been processed using different vacuum frying conditions (Table 1). The vacuum fried products processed comprised of fruits, vegetables, fish and wheat-based snacks. Some of the studies recommended optimized conditions for a number of products including apple, apricot, carrot, grass carp, gold and green kiwifruits, mushrooms, potato and shallots. Generally, the higher the frying temperature the shorter the frying time. However, there was a wide range of vacuum pressures used ranging from 1.33 to 90 kPa with more than half of the process carried out at lower than 10 kPa. Many of the products were not centrifuged after vacuum frying so would be expected to have higher oil content. For the vacuum fried products that were centrifuged, these were undertaken either within the frying chamber or outside it, using speeds of 140-1000 rpm for 2-10 minutes.

The results indicated that the vacuum frying conditions (temperature and time) for various food products varied considerably. There was also a wide variation in the vacuum pressures used. The choice of the vacuum frying conditions for the food

samples were dictated by, for example, the structure, moisture and sugar content, shape and size and pre-treatment used. Therefore, there was no other way to come up with a vacuum frying process for a specific product except to carry out experiments to obtain an optimized process.

Oil uptake of vacuum fried foods

Andres-Bello *et al*. (2011) discussed the reduction of oil uptake in vacuum fried foods. They produced a table showing the effect of vacuum frying on oil uptake and/or minimal oil absorption of several vacuum fried products at the bubble end point. They pointed out that the vacuum frying technology can be considered as a viable option to produce novel snacks with low oil content.

The various mechanisms affecting oil uptake during the vacuum frying of foods have been covered in the review paper by Dueik and Bouchon (2011a). They also presented various studies on the oil uptake of different food products and concluded that there was less oil uptake in vacuum fried products compared with traditional fried products. Furthermore, they pointed out that oil uptake appeared to be related to moisture content, with the oil content directly proportional to moisture loss.

Dueik *et al.* (2012b) presented a microstructural approach to understanding oil absorption during vacuum and atmospheric frying. They tried to understand the relationships between key microstructural parameters and oil absorption after atmospheric and vacuum frying of carrots, apples and potatoes. The effect of drainage and centrifugation on oil-uptake reduction was also analysed. Overall, a linear relationship was found between porosity and oil content in vacuum and atmospheric fried

products. However, this relationship could not be extended when analysing the whole data set, since oil absorption was significantly higher in the atmospheric fried chips. Centrifugation, however, resulted in a reduced oil uptake of up to 73% in atmospheric fried chips and up to 64% in vacuum fried chips.

Analysis of batch vacuum frying system for potato chips was undertaken by Pandey and Moreira (2012). They reported that the de-oiling mechanism removed more oil from the potato chip's surface when the samples were centrifuged at a higher speed for a longer time. However, for the same centrifuge and frying times, the higher the frying temperature, the higher the final oil content of the potato chips. This meant that the longer the chips remain immersed in the hot oil after most of the water had evaporated, the higher the oil absorption during frying. Therefore, short frying time and/or longer centrifuging time combinations would maximize oil removal from the chip's surface during the process. Furthermore, the pressurization rate was an important additional factor in the de-oiling process of vacuum fried potato chips. If the chips were de-oiled at a lower centrifuge speed (300 rpm for 40 s), a low pressurization rate (25% open valve) can aid in the removal of the chip's residual surface oil, thus resulting in lower final oil content than the chips centrifuged at higher speeds. The pressurization rate has no effect on the de-oiling process when the chips were centrifuged at a high speed (750 rpm) for 40 s.

A combination of moderate vacuum frying with high vacuum drainage and the relationship between process conditions and oil uptake in potato chips was studied by Haizam *et al.* (2013). Potato chips were vacuum fried using two operating conditions (140°C, 20 kPa and 162°C, 50.67 kPa) until the moisture content reached 10-15% (wet basis) before the samples were held in the head space under high vacuum level (1.33 kPa). The two stage process was found to significantly lower the amount of oil taken up by the potato chips by an amount as high as 48%, compared to drainage at the same pressure as the frying pressure. They explained that reducing the pressure value to 1.33 kPa reduced the water saturation temperature (11°C), causing the product to continuously lose moisture during the course of drainage. The continuous release of the water vapour prevented the occluded surface oil from penetrating the product structure and released it from the surface of the product. When frying and drainage occurred at the same pressure, the temperature of the product fell below the water saturation temperature soon after it was lifted out of the oil, which resulted in oil getting sucked back into the product.

The results revealed that the centrifugation of potato chips after vacuum frying led to a lower oil content in the final product. The use of a short frying time and/or longer centrifuging time combinations would maximize oil removal from the potato chip's surface during the process. If the chips were de-oiled at a lower centrifuge speed, a low pressurization rate can aid in the removal of the chip's residual surface oil, thus resulting in lower final oil contents than the chips centrifuged at higher speeds. The pressurization rate has no effect on the de-oiling process when the chips are centrifuged at higher speed for the same time. A combination of moderate vacuum frying with high vacuum drainage can lower considerably the amount of oil taken up by the potato chips compared to drainage at the same pressure as the frying pressure.

Changes in the oil during vacuum frying

Crosa *et al.* (2014) investigated the effect of vacuum frying and traditional frying on oil degradation, fatty acid composition and alpha-tocopherol content. Two different refined sunflower oils (SO) were used: SO with high oleic acid content (HO-SO) and SO with synthetic antioxidant (tertiary-butylhydroquinone) (TBHQ-SO). Oil degradation was monitored by measuring the free fatty acids (FFA), peroxide value (PV) p-anisidine (p-AV), total polar compounds (TPC) and oxidative stability (OS). Oil samples were taken every four hours of frying during 10 consecutive days. The values of FFA, p-AV and TPC using TBHQ-SO with traditional frying were 0.201, 207.0 and 25.0, respectively, significantly higher than the obtained values with vacuum frying at 0.073, 25.8 and 11.2, respectively. The same parameters using HO-SO were 0.327, 82.0 and 21.9, respectively, with traditional frying and they were 0.099, 33.3 and 6.4, respectively with vacuum frying. The OS was 2.44 and 7.95 with TBHQ-SO traditional frying and vacuum frying, respectively, and with HO-SO they were 0.65 and 2.67, respectively. The polyunsaturated fatty acid percentage decreased in all treatments except in TBHQ-SO vacuum frying. At the end of the frying process, the alpha-tocopherol reduction from TBHQ-SO with vacuum frying was 4.90%, TBHQ-SO with traditional frying was 53.62%, HO-SO with vacuum frying was 96.87% and HO-SO with traditional frying was 99.76%.

The results showed that the use of TBHQ in vacuum frying resulted in a high effective antioxidant activity. The FFA, p-AV and TPC were lower for the oil used in vacuum frying rather than in traditional frying regardless of the sunflower oil used (TBHQ-SO or HO-SO). However, the oil stability was lower in traditional frying than in vacuum frying. The

polyunsaturated free fatty acid percentage and alpha-tocopherol changes in TBHQ-SO vacuum frying oil were not significant. These suggested that the usage time for the oil with the vacuum frying process will be much longer compared with the traditional frying process.

Packaging and storage of vacuum fried foods

Vacuum fried foods need to be packaged properly in order to maintain their qualities, especially texture. These products were also prone to rancidity because of their oil contents. Surprisingly, there were few studies on the packaging and storage of vacuum fried foods.

Fan *et al.* (2007) reported on the storage stability of carrot chips. They packaged vacuum fried carrot chips in 25-μm low-density polyethylene (LDPE) film with 95% nitrogen gas. The packages were then stored in the dark at 0, 10, and 25°C for up to six months. Their results indicated that storage time, temperature and the interaction between the time and temperature had a significant effect on the moisture content and water activity of the carrot chips. However, only the storage time and temperature significantly affected the fat content of the products. The fat content in carrot chips might increase the carotenoid bioavailability but the shelf life might decline because of lipid oxidation. The breaking force of the products increased with increased storage time and temperature which should be lower for crisp chips since it would easily break. When increasing the storage temperature and time, the β-carotenoid and ascorbic acid contents of carrot chips decreased. The acid value of the products increased with increasing storage temperature and time. The estimated shelf lives of carrot chips, defined by the time when the acid value is equal to 3 mg/g for temperatures of 25, 10 and 0°C were 8.8, 23.4 and 55.3 months, respectively.

A study was carried on the lipid stability of dehydrated (vacuum fried) beef strips stored in polyethylene (PET) and aluminium foil laminate (AFL) packaging with nitrogen flushing by Presswood (2012). The moisture content and water activity of the product were only affected following storage in PET packaging. Lipid decomposition was evidenced by significant increases in free fatty acids (FFAs) for both packaging types and Totox value with PET packaging, though these changes were considered to be minor with FFAs reaching 4.0% (Oleic acid) during 17 weeks of storage at 25°C. Using derived mathematical models, the FFAs was predicted to increase to over 8% (Oleic acid) and the Totox value not exceeding 32 even after 32 weeks of storage at 15-25°C. There were no significant changes in the unsaturated fatty acid content but the levels of polyunsaturated fatty acids, linoleic and linolenic acids decreased during the 17 weeks of storage, and average levels were higher in the AFL packaging, indicating that less oxidation occurred. The tocopherol content decreased significantly from initial concentrations and mean levels were higher in the oil from the products stored in AFL packaging. Sterol oxidation products were higher in the oil from products stored in PET packaging. The results of the experiments suggest that vacuum fried beef strips can be stored up to 32 weeks at 15-25°C without significant lipid deterioration. Aluminium foil laminate packaging reduced most of the changes that occurred due to lower oxygen and water vapor transmission rates.

The results suggested that vacuum fried products can be packaged in LDPE, PET or AFL bags with nitrogen flushing and would have an acceptable shelf life at ambient conditions. However, the two important qualities that dictate the shelf life of vacuum fried products were crispness and rancidity. Since AFL had lower oxygen and water vapor transmission rates, it was therefore recommended for use with nitrogen flushing in packaging of vacuum fried products.

Conclusions

The vacuum frying systems available varied in designs but still consist of the same basic parts, namely: a) a vacuum frying chamber; b) a condenser; and c) a vacuum pump. The method of heating the oil in the frying chamber can be gas, steam or electricity. The condenser used water or refrigeration to condense the steam evolved during frying. The vacuum pump used can be a liquid ring vacuum pump or an oil-sealed vacuum pump. In addition, some vacuum frying systems incorporated a means of centrifuging the fried samples within the frying chamber.

The vacuum frying process required the heating of oil to the required temperature. Then the sample to be processed was placed on the basket inside the frying chamber and suspended above the hot oil. The pressure inside the vacuum frying chamber was reduced to the required pressure; the sample was then lowered into the hot oil for the required duration; the basket was raised above the oil and then centrifuged within the chamber for the required speed and time or can be taken out of the frying chamber and centrifuged using a separate machine. The product was placed on absorbent paper, cooled and packed in an aluminium laminate bag with or without nitrogen flushing.

There was a rapid increase in temperature of the product toward the boiling point of water (at the

associated pressure) then a steady increase towards the temperature of the oil during vacuum frying. The rate of moisture loss of the product during vacuum frying can be divided into two parts: the constant rate and falling rate periods of drying. The convective heat transfer coefficients during vacuum frying of potato at low pressure were much lower than during vacuum frying at moderate pressures. The average temperature of potato during vacuum frying rapidly increased and reached a plateau before approaching the oil temperature. Regardless of the frying pressure, the potato core experienced pressures of approximately 40 kPa higher than at the surface.

The vacuum frying conditions (temperature and time) for various food products varied considerably and there was also a wide variation in the vacuum pressures used. The choice of the vacuum frying conditions for the food samples was dictated by a range of physical parameters, as well as pre-treatment conditions. Therefore, there was no other way to design a vacuum frying process for a specific product except to carry out experiments to obtain an optimized process.

The centrifugation of potato chips after vacuum frying lead to lower oil content in the final product. The use of short frying time and/or longer centrifuging time combinations would maximize oil removal from the potato chip's surface during the process. If the chips were de-oiled at a lower centrifuge speed, a low pressurization rate can aid in the removal of the chip's residual surface oil, resulting in lower final oil contents compared with chips centrifuged at higher speeds. The pressurization rate had no effect on the de-oiling process when the chips were centrifuged at a higher speed for the same time duration. A combination of moderate vacuum frying with high vacuum drainage can lower considerably the amount of oil taken up by the potato chips compared to drainage at the same pressure as the frying pressure.

The use of TBHQ in vacuum frying gave high effective antioxidant activity. The FFA, p-AV and TPC were lower for oil used in vacuum frying than in traditional frying regardless of the sunflower oil used (TBHQ-SO and HO-SO). However, the oil stability was lower in traditional frying than in vacuum frying. The polyunsaturated free fatty acid percentage and alpha-tocopherol changes in TBHQ-SO vacuum frying oil were not significant. The results suggested that usage time of the oil with the vacuum frying process will be much longer compared with the traditional frying process.

There were two important qualities that dictate the shelf life of vacuum fried products, crispness and rancidity. Hence it was recommended to use aluminium foil laminate bag with nitrogen flushing in packaging of vacuum fried products.

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