DEVELOPMENT OF FINISH COOKING METHODS FOR
PRODUCING LOW-FAT BREADED CHEESE STICKS

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FAT BREADED CHEESE STICKS

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ABSTRACT

Deep-fat fried foods have unique characteristics that attract consumers but their high fat contents must be reduced in order to provide healthy foods along with high quality. In the first part of this study, effects of frying temperature and frying pressure on the quality of partially fried breaded cheese sticks were determined. In the second part, far infrared finish cooking methods were compared to traditional deep-fat frying in terms of product quality.

Increasing frying temperature significantly (P<0.05) reduced fat and moisture contents of the samples and increased crispness and exterior hardness. Pressure did not affect crust fat content of the samples significantly (P>0.05). However, increasing frying pressure resulted in the samples having higher moisture contents. Crispness and exterior hardness of pressure-fried cheese sticks were lower than traditional deep-fat fried samples. Increasing frying temperature and pressure resulted in darker sample color.

Par-fried far-infrared finish cooked cheese sticks had lower fat contents than deep-fat fried cheese sticks had. Moisture contents of far-infrared finish-cooked samples were higher than those of deep-fat fried samples. Far-infrared finish cooking significantly (P<0.05) reduced crispness and exterior hardness of breaded cheese sticks.
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CHAPTER 1:

Introduction

Deep-fat frying is a widely used cooking method that produces flavorful, appealing foods. A large variety of foods including potato, apple, carrot, chicken, fish, and donuts are being fried in all parts of the world. However, fried foods have high fat contents and excessive consumption of fried foods may lead to serious health issues such as obesity and heart diseases.

Pre-frying, frying, and post-frying factors have been manipulated in many studies to limit fat absorption in fried foods (Ziaiifar, Achir, Courtois, Trezzani, & Trystram, 2008). It has been reported that increasing frying temperature may reduce fat uptake and produce crispy products (Kita, Lisinska, & Golubowska, 2007; Moyano & Berna, 2002). Frying under high pressure is also known to produce tender, juicy foods with low fat content (Bengston, 2006; Innawong, 2001).

Finish cooking of foods after a par-frying step is another method for producing low fat foods. Infrared heating, microwave cooking, usage of superheated steam, and combinations of them have been patented by some researchers (August, 1991; Fosb, Korremann, & Ullum, 1998; Walsh, Kester, Corrigan, & Elsen, 2000). Lloyd, Farkas, and Keener (2004) used a controlled dynamic radiant oven to create a heat flux profile which can be observed during deep-fat frying. It was concluded that samples cooked in the radiant oven had overall acceptability with lower fat contents.

1.1 Hypothesis

The hypothesis is that increased frying temperature and pressure will limit fat absorption of fried foods and maintain high quality and there will not be a difference between far-infrared finish cooking and deep-fat frying in terms of product quality.
1.2 Objectives

The goal of this research was to investigate the effects of frying temperature, frying pressure and finish-cooking methods on the quality of par fried frozen cheese sticks. The specific objectives were as follows:

1. Evaluate the effects of frying temperature and pressure on the quality of breaded cheese sticks in terms of fat and moisture contents, crispness, exterior and interior hardness, and color.

2. Develop far-infrared finish-cooking methods that can produce low fat high quality breaded cheese sticks

1.3 Rationale and Significance

There is an increasing demand for healthy foods from consumers and fried foods with high fat contents tend to be perceived as unhealthy. Reducing fat uptake while maintaining other quality attribute is still a challenging task for the food industry. This study was conducted to determine frying factors that can limit fat absorption and to develop a finish-cooking method for producing low-fat high-quality foods.
1.4 References


CHAPTER 2:

Literature Review

Deep-fat frying is a well-known and common cooking method in which food products are immersed in different varieties of hot edible oils (Hubbard & Farkas, 2000). Large varieties of foods are being deep-fat fried all over the world and they are very popular due to their appealing crispy crusts and flavor (Mallikarjunan, et al., 2009).

2.1 Frying Process

Deep-fat frying is a widely used food processing method to cook foods such as French fries, potato chips, chicken nuggets, fish sticks, and doughnuts. One of the main functions of frying oil is to supply heat to the food that is going to be fried. Frying oil also improves flavor and mouth feel of fried products. When a food material is immersed in hot oil, which is generally between 140°C and 180°C, the temperature at the surface of the material rapidly increases and water at the surface starts boiling. As temperature inside the food increases, the sample will be eventually cooked. During deep-fat frying, protein denaturation, starch gelatinization, color development, shrinkage occur along with a porous, crispy crust formation (Mellama, 2003; Mir-Bel, Oria, & Salvador, 2009; Ziaiifar, et al., 2008).

2.2 Frying Mechanism

Deep-fat frying is a complex process which involves simultaneous heat, moisture, and fat transfer between food products and frying oil. In general, heat is transferred from oil to food surface via convection while it’s transferred within the food sample by conduction (Mallikarjunan, et al., 2009).

Farkas (1994) described a heat transfer model which divides frying into four stages:
1. Initial heating: In this stage, the surface temperature of food material reaches the boiling point of surface water in the material. Heat is transferred from the oil to the material surface by free convection while conduction takes place to transfer heat to the core part. Initial heating lasts a very short time and water loss is negligible.

2. Surface boiling: Forced convection replaces free convection in this stage. Water loss at the surface and crust formation begins. Due to the vapor release, bubbles that can be seen during frying increases turbulence of oil around the food surface.

3. Falling rate: The food material losses most of its moisture and internal temperature approaches boiling point of water. The thickness of the crust increases which in return decreases heat transfer rate. Vapor release from the material also decreases. This stage is the longest stage of all.

4. Bubble end-point: No bubble escape can be detected in this stage. Moisture loss may be completed and the heat transfer rate decreases.

Heat transfer during deep-fat frying is affected by many factors. Conduction within food material depends on thermal properties of the sample. Density, specific heat, thermal conductivity, and thermal diffusivity are important for conduction heat transfer within food material. According to Newton’s law of cooling

\[
q'' = h(T_\infty - T_s)
\]

where \( q'' \) is the heat flux (W/m\(^2\)), \( h \) is the convective heat transfer coefficient (W/m\(^2\)°C), \( T_\infty \) is frying oil temperature (°C) and \( T_s \) is surface temperature of the food (°C), the temperature difference between the frying oil and food sample is the driving force for convection. Heat transfer rate is influenced by the heat transfer coefficient which changes with oil temperature, heat capacity, viscosity and surface tension (Mallikarjunan, et al., 2009). Mariscal and Bouchon
(2008) used the term of thermal driving force to compare atmospheric and vacuum frying. They defined the term as temperature difference between the oil temperature and boiling point of water under the working pressure.

As for fat uptake, different theories have been proposed to explain the mechanism. During deep-fat frying, food products which have high moisture contents at the beginning lose high levels of moisture and overpressure is created inside the product. These water escapes and overpressure prevents fat absorption when the food product is still inside hot oil. According to Moreira, Sun, and Chen, (1997), 64% of oil is absorbed after the food product is removed from hot oil and when it starts cooling. After the food product is removed from hot oil, its internal temperature decreases, and the steam that is still inside the product condenses. Due to the condensation, a vacuum effect occurs and surface oil is sucked into the product (Ziaiifar, et al., 2008). Ziaiifar, et al., (2008) also stated that this mechanism was observed for a food model system by Vitrac, (2000). On the other hand, it is concluded that the condensation mechanism may be valid for deep-fat frying of large food samples for short time periods (Mellama, 2003).

Fat uptake in fried foods could also be related to capillary forces. Capillary movement of liquids can be seen in narrow pores where liquid can flow against gravity. The crust of a fried food is highly porous and when a fried food is removed from hot oil, the pores are filled with water vapor. During cooling period, interfacial tension between frying oil on the product surface and vapor increases since temperature is decreasing which results in increased capillary pressure. Increased capillary pressure eventually lets surface oil to penetrate the pores. According to this theory, pore radius and surface tension are important factors for fat uptake. Small pores and high surface tension may accelerate fat uptake in fried foods (Moreira & Barrufet, 1998; Ziaiifar, et al., 2008).
Ufheil and Escher (1996) used potato slices to study fat uptake dynamics. They found that 80% of oil was absorbed after removing of the samples from hot oil. It was concluded that the relationship between fat adhesion onto food as well as drainage from food surface were involved in the mechanism. Factors such as product size and frying time should be studied in details for this theory.

2.3 Frying Oil

Frying oil has important effects on both functional and sensory characteristics of fried food products (Mallikarjunan, et al., 2009). Edible oils such as soybean, canola, sunflower, corn, peanut, and blends of animal and vegetable oils are being used for deep-fat frying and each oil has different characteristics. Selection of oil for deep-fat frying depends on the characteristics of oil, cost, and product type (Blumenthal & Stier, 1991).

During deep-fat frying, chemical reactions such as hydrolysis, polymerization, pyrolysis, oxidation, and physical changes such as color darkening, increased viscosity and foaming, and decreased viscosity occur and oil quality decreases (Innawong, 2001).

Blumenthal (1991) studied the effects of oil quality on French fries. When edible oils are used for deep-fat frying, they go through the following steps which explain the degradation mechanism:

1. Break-in-oil: Foods fried at this stage are considered raw, light in color and less crispy. A lesser amount of oil is absorbed and no cooking odor is detected.

2. Fresh oil: Foods are partially cooked and crispy. Browning starts and oil absorption slightly increases.

3. Optimum oil: Foods are fully cooked and have crispy, golden brown crusts. Frying odor is present and oil absorption is at its optimum level.
4. Degrading oil: Product surfaces become dark, hard and spotted. Oil absorption is excessive.

5. Runaway oil: Food products are excessively oily with dark, hard surfaces. The products are also not fully cooked and have off-odors.

Frying oils must be discarded after degradation products such as aldehydes, polymers, mono-glycerids, and free fatty acids start forming and reach a hazardous level. However, there is no standard regulation explaining when to discard frying oil. Paul and Mittal (1997) proposed 5 conditions telling when frying oil should be discarded.

1. Frying oil must have acceptable organoleptic characteristics.
2. Total polar materials must not be over 25% of total mass.
3. Acid value of the oil should not be higher than 2.5.
4. Smoke point of the oil must be over 170 °C.
5. Frying temperature should not be over 180 °C.

To determine frying oil quality and have an idea of oil degradation physical and chemical tests can be conducted. In physical tests, viscosity, color, foaming, dielectric constant, and ultraviolet absorption can be measured. Acid value, iodine value, peroxide value, free fatty acids, and total polar materials can be determined during chemical tests. Commercially available quick test kits which are based on measuring a chemical change in oils are also available. Innawong et al. (2004) developed a chemosensory system and measured oil rancidity. It was reported that the chemosensory system could successfully indentified different oil types and good correlation was obtained between chemical characteristics and signals of the system. There is no agreement on which method is the best for determining oil quality but total polar component is believed to be the most suitable indicator of oil quality (Innawong, et al., 2004). Du Plessis and Meredith
(1999) concluded that dielectric constant and free fatty acid are correlated well with total polar component level so that they may be used to monitor oil quality.

2.4 Reducing Fat Uptake in Fried Foods

Deep-fat fried foods may have fat contents up to 1/3 of their total mass. Besides their appealing characteristics, a high amount of fat is not desirable and fried foods may be perceived as unhealthy since excessive consumption of fat is linked to the development of heart disease and obesity (Bengston, 2006; Mellama, 2003). The food industry has been trying to reduce fat uptake in fried foods while maintaining high quality (Mallikarjunan, et al., 2009). Many factors in pre-processing, processing, and post-processing steps have been manipulated to reduce fat uptake.

2.4.1 Pre-Frying Factors

Linear relationship between surface area and volume of food products have been reported (Gamble, Rice, & Selman, 1988). Foods with high surface area to volume ratio tend to have higher fat contents than products with a small surface area to volume ratio (Paul & Mittal, 1997). However, Tajner-Czopek et al. (2007) found that fat content of French fries (10 mm x 10 mm) was higher than the fat content of French fries of 8 mm x 8 mm which had higher surface area to volume ration. It was concluded that short frying time of 8 mm fries was more effective than sample size in this situation.

Blanching before frying is done by immersion food products into boiling water or using hot steam. The mechanism of blanching on reducing fat content is not clear. It is stated that blanching can increase moisture content of foods because of the release of water soluble materials. Increase in moisture content may lead to an increase in fat content. On the other hand, blanching can gelatinize starch on the food surfaces which can form a thin film preventing fat
absorption (Ziaiifar, et al., 2008). Aguilar et al. (1997) stated that low temperature long 
blanching (55-70 °C, 15-60 min.) of potatoes in water reduced fat content and it may be due to 
the activation of pectin-methyl-esterase enzyme which was assumed to reduce porosity.
Blanching at high temperatures for short time was found to increase fat uptake (Alvarez, Morillo, 
& Canet, 2000; Pedreschi & Moyano, 2004).

It has been shown that drying food samples before frying has the ability of reducing fat 
content and improving texture. Water loss during drying of food materials decreases total frying 
time and fat absorption is limited in an indirect way. Shrinkage is also observed in dried foods 
which allows less open pores to be present which in return reduces fat uptake (Van Loon et al., 
2006). Sobukola et al. (2009) investigated the effect of convective hot air drying on yam slices 
and concluded that low initial moisture content limited fat uptake during frying. Debnath et al. 
(2003) also used hot air drying and concluded that pre-fry drying decreased moisture and oil 
transfer coefficients. Sensory attributes of the pre-fry dried ribbon snacks were not different than 
the samples fried without drying except for appearance. Hansen (1997) reported that microwave 
drying produced darker fried onion slices with lower fat contents compared to the onion slices 
dried with hot air. Fat uptake in French fries prepared with vacuum-microwave drying was less 
than fat uptake in French fries dried with convective air drying (Tajner-Czopek, Figiel, & 
Carbonell-Barrachina, 2007). Osmotic dehydration is another method to limit fat uptake in fried 
foods. When food products are immersed in concentrated sugar or salt solutions, water inside 
food products starts transferring to the solution and some of the solids in the concentrated 
solution are absorbed. Due to the decreased moisture content, reducing fat content was observed 
by many researchers (Fan, Zhang, & Mujumdar, 2006; Krokida, Oreopoulou, Maroulis, & 
Marinos-Kouris, 2001; Sahin, Sumnu, & Oztop, 2007).
Coating applications may improve appearance, flavor and texture as well as weight and volume (Cunningham & Suderman, 1981; Fiszman & Salvador, 2003; Mohamed, Hamid, & Hamid, 1998). Food products can be coated with edible films, batter and breading or a combination of both. Coating is known to limit moisture loss as well as fat uptake (Mellama, 2003).

Different ingredients such as collagen, caseins, carboxy methylcellulose, methylcellulose and whey protein isolate can be used for edible film coating of food products. Edible films have the potential of reducing fat uptake and moisture loss. They may also increase crispness of fried products since they can limit moisture transport from the core part to the crust (Ballard, 2003). Mallikarjunan et al. (1997) used corn zein, hydroxypropyl methyl cellulose, and methyl cellulose solutions to coat mashed potato balls. Fat reduction up to 83.6% was observed in fried edible-coated potato balls. Ballard (2003) found that the effects of methylcellulose and whey protein isolate were significant on fat content of chicken nuggets. Methylcellulose coated samples had less fat content than both the control and whey protein isolate coated samples had.

Batters and breading are like barriers that prevent moisture loss during cooking so a final product can be produced which is tender and juicy on the inside and crispy on the outside. Breading and battering can also limit fat uptake. Starches, wheat and non-wheat flours, hydrocolloids, proteins, dextrins, and fibre sources may be used in batter formulations (Fiszman & Salvador, 2003). Using different batter formulations also have significant effects on fat content of fried foods. Akdeniz et al. (2006) used hydroxypropyl methlcellulose (HPMC), xanthan and guar gum in batter formulation to evaluate their effects on product quality. It was found that all gums were effective to control fat uptake and resulted in 53% fat reduction when
they were used in combination. Batter formulation including pregelatinized tapioca starch reduced fat content of carrot slices (Akdeniz, Sahin, & Sumnu, 2005).

Particle size of breading materials should be considered for coating applications. Moreira et al. (1997) prepared tortilla chips from masa flour which had different particle size distribution. Using smaller particle size distribution resulted in high fat contents in tortilla chips. Maskat and Kerr (2002) coated chicken breasts with crackermeal breading. Three different particle sizes, small (particle size $\leq$ U.S. No. 60 mesh), medium (particle size between U.S. No. 20 and 60), and large (particle size $\geq$ U.S.No. 20) were used. Increasing particle size decreased fat content of chicken breasts significantly.

2.4.2 Frying Factors

2.4.2.1 Frying Time

Gamble et al. (1987) reported that both moisture loss and fat uptake were proportional to the square root of frying time. Makinson et al. (1987) deep-fat fried twenty animal and plant food products and found that fat content of the food products except beef sausage increased with increased frying times. Reddy and Das (1993) reported that increasing frying time increased fat content of potato chips. Food products have been fried for either constant time or until reaching a certain core temperature or final moisture content to study fat uptake by researchers (Innawong, 2001; Troncoso, Pedreschi, & Zuniga, 2009).

2.4.2.2 Frying Temperature

Gamble et al. (1987), Reddy and Das (1993), and Moreira et al. (1997) found that fat was independent of frying temperature. However, there are contradictory results in the literature. Pedreschi and Moyano (2005) reported that low frying temperatures resulted in high fat uptake in potato slices fried between 120 °C and 180 °C. Moyano and Berna (2002), and Kita et al. (2007)
also concluded that increasing frying temperature decreased the fat content of foods. At lower frying temperatures frying time is prolonged and a soft crust forms which may lead to high fat uptake. On the other hand, Mallikarjunan et al. (1995), Moreira et al. (1995), and Innawong (2001) stated that fat content of fried foods increases with increasing temperature.

2.4.2.3 Frying Pressure

Working pressure during frying has been manipulated to reduce fat uptake in fried foods. When vacuum is applied during frying, the boiling point of water is reduced and moisture loss starts earlier but the rate of moisture loss doesn’t change. Besides reducing fat absorption, lower frying temperatures can be used and fried products could preserve original color and flavors during vacuum frying. Reducing oxygen content during frying may also extend life time of frying oil (Da Silva & Moreira, 2008).

Mariscal and Bouchon (2008) vacuum fried apple slices under 0.15 bar. To compare vacuum frying and atmospheric frying, they defined the thermal driving force as the temperature difference between the boiling point of water at the working pressure (0.15 bar) and frying oil temperature. The same thermal driving forces were applied during the experiments. Thus, when atmospheric frying was conducted at 140, 150 and 160 °C, which corresponded to 40, 50, and 60 °C thermal driving forces, vacuum frying temperatures were adjusted to 95, 105, and 115 °C to ensure that the same thermal driving forces were achieved. They found significant reduction of fat uptake when samples were analyzed under the same thermal driving force.

Tan and Mittal (2006) vacuum fried donuts and fat content of vacuum fried donuts were found to be higher than fat content of donuts fried under atmospheric pressure. Bengston (2006) fried breaded fish sticks at 41 kPA. Both crust and core fat contents of fish sticks were higher than those of fried fish sticks under atmospheric pressure. Due to the equipment available in that
research, samples were dipped into frying oil and then vacuum was applied. It was concluded that when cooking was complete and pressure increased from vacuum to atmospheric level, products were still in the frying oil which could have accelerated fat uptake.

Deep-fat frying under high pressure is one of the methods that food industry has been using. Deep-fat frying under high pressure raises the boiling point of both water in food products and frying oil. Food products fried under high pressure are juicer and more tender than traditional fried foods. The heat transfer rate is increased during frying under high pressure (Mallikarjunan, et al., 2009). Erdogdu and Dejmek (2010) concluded that frying under high pressure (2 bars) increased heat transfer coefficient but boiling heat transfer correlation was not good enough to predict heat transfer in pressure frying.

Restaurant-type pressure fryers require a large food load to create enough steam to build up pressure. This situation may cause a lot of waste and oil quality may be degraded more quickly because of steam. Innawong (2001) modified a pressure fryer to allow external pressurizing medium such as nitrogen or compressed air to be used instead of steam generated by foods. The exhaust tube of the pressure fryer was replaced with a T-shaped tube which was connected to the gas hose of the fryer. Pressure level inside the fryer was adjusted with the combination of specific dead weights, fryer orifices and a safety relief.

Innawong (2001) deep-fat fried chicken nuggets under 101 kPa, 163 kPa, and 184 kPa to compare pressure frying and atmospheric frying. Increasing pressure above atmospheric level increased moisture retention and decreased fat uptake. Nitrogen was used as pressurizing medium and product quality wasn’t different than the situation when steam was the pressurizing medium. Degradation of frying oil was also slowed down when nitrogen was used for building up the pressure.
Ballard (2003) also compared nitrogen and steam for their suitability as the pressurizing medium. No significant differences were found between nitrogen and steam in terms of product quality. Bengston (2006) compared compressed air to nitrogen. No difference between the use of compressed air and nitrogen as pressurizing medium was detected. Using compressed air resulted in higher moisture contents in breaded fish sticks. Fish sticks fried under high pressure had lower fat contents than fish sticks fried at atmospheric pressure. Yusop et al. (2009) fried chicken nuggets at 102 and 156 kPa. According to the sensory evaluation of the samples, chicken nuggets fried at 156 kPa were preferred to those fried at 102 kPa by trained panelists.

2.4.3 Post-Frying Factors

Most of the fat absorption happens after foods are removed from frying oil. Thus, different applications have been developed to limit fat uptake in this period. Moreira et al. (2009) developed a de-oiling mechanism to reduce fat uptake in fried foods. Frying basket was attached to a centrifuge system and when the basket was raised from frying oil, the samples was rotated for 40 s. at 770 rpm. This system was used during vacuum frying of potato chips and it was reported that approximately 86% of oil could be removed before the pressure inside the fryer reached atmospheric level. Mir-Bel et al. (2009) proposed that vacuum breaking velocity played an important role on fat absorption of vacuum fried foods. They concluded that increasing vacuum breaking velocity decreased fat content of potato chips by up to 69.8%.

Fat uptake can also be limited if foods fried for short times and finish cooked with different methods. Many patented works have been developed by using this approach (August, 1991; Fosb, et al., 1998; Masaki, 2006; Walsh, et al., 2000). These studies were based on the limitation of frying time and creating a de-oiling effect (Ziaiifar, et al., 2008). Hot air, superheated steam, and infrared energy were used to finish cook the samples after par-frying.
Among these heating methods, infrared heating was one of the easiest and most effective one to control and use for producing low-fat food products.

2.5 Infrared Radiation

Infrared radiation is a type of electromagnetic radiation and energy is transferred in the forms of waves by infrared radiation. Infrared radiation can be divided into three regions in terms of the wavelength. Near-infrared (0.78 - 1.4 µm), mid-infrared (1.4 – 3 µm), and far-infrared (3-1000 µm) are the three regions of infrared radiation (Sakai & Hanzawa, 1994). Different types of materials can be used to produce infrared radiation at those regions. In a general perspective, tungsten filaments which can operate at temperatures around 2000 °C are used to produce near-infrared radiation. The temperature range of quartz tubes can be between 700 and 1150°C and mid-infrared radiation can be emitted. Ceramics are usually suitable for far-infrared radiation and they are run below 800°C (Rao, Rizvi, & Datta, 2005).

Any material at temperatures above absolute 0 can emit infrared energy. Most of the infrared energy is emitted by the molecules which are very close (1 µm) to the material surface. Thus, infrared radiation is considered to be a surface phenomenon. An ideal surface which is called a blackbody may absorb all incident radiation and emit infrared energy better than any other surface. Infrared energy emitted by a blackbody is also independent of direction. However, no real blackbody is present (Incropera & DeWitt, 1996).

The Stefan-Boltzman law describes heat flux (emitted energy per unit area) emitting from a real surface as follows:

\[ Eb = \varepsilon \sigma T_s^4 \]

where \( \sigma \) is the Stefan-Boltzman constant (5.669 x 10^-8 W/m²K^4), \( T_s \) is absolute surface temperature (K), and \( \varepsilon \) is emissivity. Emissivity is the ratio of the radiation emitted by a real
surface to the radiation emitted by a blackbody. Emissivity of a material can be between 0 and 1 (Incropera & DeWitt, 1996).

Spectral distribution of infrared energy is another important factor and it is defined by Planck. For a blackbody, the Planck’s law is

$$E_b, \lambda (\lambda, T) = \frac{2\pi hc^2}{\lambda^5 [\exp(hc/\lambda kT) - 1]}$$

where, $h$ is the Planck constant ($6.6256 \times 10^{-34}$ J.S), $k$ is the Boltzmann constant ($1.3805 \times 10^{-23}$ J/K), $c$ is the speed of light in vacuum, $T$ is the absolute temperature of the blackbody (K) (Rao, et al., 2005). According to the Planck’s law, emitted infrared energy is given a function of wavelength and at any wavelength emitted radiation increases with increased temperature. On the other hand, Wien’s displacement law describes at what wavelength the maximum spectral distribution is achieved.

$$\lambda_{\text{max}} = \frac{2897.8 \, \mu m.K}{T}$$

where $\lambda_{\text{max}}$ is the peak wavelength ($\mu$m), $T$ is temperature (K) (Incropera & DeWitt, 1996).

When heat transfer occurs between two objects, it won’t be accurate to assume all emitted energy by the high temperature surface is absorbed by the other surface. In this case, net radiant energy transfer between two materials is given by

$$q_{1-2} = \sigma A_1 \varepsilon_{1-2} (T_{A1}^4 - T_{A2}^4)$$

where $T_{A1}$ and $T_{A2}$ are the surface temperatures of material 1 and material 2, and $\varepsilon_{1-2}$ is a combined factor for shape and emissivity. Combined factor accounts for the emitted energy that is not absorbed by the low-temperature surface and emissivity values of the surfaces. It can be calculated according to the following formula:

$$\varepsilon_{1-2} = \frac{1}{\frac{1}{F_{1-2} + \left(\frac{1}{\varepsilon_1} - 1\right) + \frac{A_1}{A_2} \left(\frac{1}{\varepsilon_2} - 1\right)}}$$
where \( F_{1-2} \) is the shape factor, \( \varepsilon_1 \) and \( \varepsilon_2 \) are the emissivity values for material 1 and 2, \( A_1 \) and \( A_2 \) are surface areas of material 1 and material 2 (Singh & Heldman, 2009).

When infrared energy incidents on an object, some of the energy is absorbed, reflected or transmitted. The values of absorptivity, reflectivity, and transmissivity are between 0 and 1; and the sum of all three is equal to 1.

\[
\rho + \alpha + \tau = 1
\]

where \( \rho \) is reflectivity, \( \alpha \) is absorptivity, and \( \tau \) is transmissivity (Rao, et al., 2005).

As for food products, water and lipids are strong absorbers of infrared energy. Lipids can absorb infrared energy especially at wavelengths between 3 and 10 µm. Wavelengths which liquid water absorbs infrared energy the most are 2.93, 4.72, 6.10, and 15.3 (Rao, et al., 2005). Near-infrared energy tends to be reflected by food products more than far-infrared energy does. On the other hand, near-infrared energy can penetrate food products better than far-infrared energy which makes far-infrared energy applications suitable for surface heating (Krishnamurthy, Khurana, Jun, Irudayaraj, & Demirci, 2008).

**2.5.1 Infrared Heating Applications in Food Processing**

Using infrared energy, especially far-infrared region, has many advantageous for heating of food stuffs. Efficiency, rapid heating, easy control and design features are some advantageous of infrared heating (Sakai & Hanzawa, 1994).

Infrared heating has been applied for drying of food products by many researchers (Abe & Afzal, 1997; Fu & Lien, 1998; Mongpreeneet, Abe, & Tsurusaki, 2002; Nowak & Levicki, 2004). Hebbar et al. (2004), Lin et al. (2007), Nimmol et al. (2007), Pan et al. (2008) combined infrared heating with other methods such as convective drying, freeze drying, and super-heated
steam to improve dried product quality and to increase efficiency of drying process. Overall, using infrared radiation during drying was found to be very useful for drying applications.

Infrared heating has been investigated to inactivate microorganisms in food products. When infrared radiation is used for this purpose, the heating source, sample size, and target microorganism are important factors to be taken into account (Krishnamurthy, et al., 2008). *B. subtilis, B. cereus, and S. aureus* were successfully inactivated in both petri dishes and food products such as paprika under infrared radiation (Hamanaka, Uchino, Furuse, Han, & Tanaka, 2006; Krishnamurthy, et al., 2008; Sawai, Matsumoto, Saito, Isomura, & Wada, 2009; Staack, Ahrne, Borch, & Knorr, 2008).

Sheridan and Shilton (1999) investigated the effect of far infrared radiation on meat products. Far-infrared heating was selected since meat products had high fat content on the surface and far-infrared energy would be absorbed better than other infrared regions by the products. Far-infrared cooking was also compared to mid infrared cooking. Far-infrared cooking reduced cooking time, surface drying, and charring.

Uysal et al. (2009) roasting conditions of hazelnut were optimized when microwave and infrared heating were used. A microwave-infrared combination oven which had three halogen lamps (1500 W maximum power) was used in the study. When hazelnuts were roasted for 2.5 min. at 90% microwave power, 60% upper halogen lamp power, and 20% lower halogen lamp power, the quality was comparable with the quality of conventionally roasted hazelnuts.

Olsson et al. (2005) combined near infrared heating and jet impingement to bake baguettes. Combination of the two methods enhanced color development and reduced heating time. A thinner crust was formed when infrared heating was used due to the short baking time.
Methods which were claimed to produce low-fat fried like products have been patented. Some of these methods were based on finish cooking of food samples with combination of infrared and other heating methods (August, 1991; Fosb, et al., 1998; Walsh, et al., 2000). Lloyd et al. (2004) used a controlled dynamic radiant oven which can create a heat flux profile similar to the one in deep-fat frying process. The oven had 5 pairs of quartz halogen heaters mounted on both sides of the conveyor belt. Heat flux profile was adjusted by changing the distance between the halogen lamps and food sample. French fries cooked in the radiant oven had lower fat contents than deep-fat fried fries and overall acceptability of infrared finish cooked samples was similar to deep-fat fried French fries. Melito (2009) cooked par-fried donuts in a similar oven and concluded that fat absorption in donuts was limited without sacrificing any other quality attributes.

2.6 Conclusion

Deep-fat fried foods are among the most popular foods but they may also lead to increased health risks. Different methods can be used to limit fat absorption in fried foods. Pre-frying, frying, and post-frying factors can be manipulated. However, those methods should be chosen carefully to produce low-fat high quality food products.
2.7 References


CHAPTER 3:

Effects of Frying Temperature and Pressure on Quality of Breaded Cheese Sticks

3.1 Abstract

Fried foods are very popular around the world and reducing fat content to provide healthier foods to customers is still a challenge for the food industry. Frying under high pressure has been used to lower fat content of fried foods. In this research, effects of pressure levels were evaluated on breaded cheese stick quality along with frying temperature. Par-fried frozen breaded cheese sticks were fried at three different pressure levels (101 kPa, 163 kPa, and 184 kPa) and three different frying temperatures (165 °C, 175 °C, and 185 °C). Moisture and fat contents, crispness, exterior and interior hardness, and color of the samples were measured to determine the effects of pressure and frying temperature.

Changing pressure level did not affect crust fat content of the samples significantly (P>0.05). Samples fried under 163 kPa had significantly (P<0.05) higher crust moisture content than other samples had but were less crispy than samples fried under 101 kPa. Increasing frying temperature reduced crust fat content significantly (P<0.05). Frying at 175 °C and 185 °C produced samples with lower crust fat content than frying at 165 °C. Samples fried at 185 °C were crispier and darker in terms of crust color than samples fried at 165 °C and 175 °C (P<0.05).

Keywords: frying temperature, pressure, crust fat, crispness
3.2 Introduction

Deep-fat frying is one of the most common cooking methods in the world since it provides unique flavor and improves texture of foods. From potato chips to French fries, doughnuts, extruded snacks, chicken nuggets, fish sticks, and fruits and vegetables like apple, mango or carrot are being fried all over the world. One of the main characteristics of fried foods is a crispy, porous, and oily crust and a moist cooked core (Bouchon, Hollins, Pearson, Pyle, & Tobin, 2001; Da Silva & Moreira, 2008).

Besides desirable attributes, fried products are considered to be unhealthy due to their high fat contents. With increased awareness of consumers the food industry is dealing with the problem of producing low-fat fried foods with high quality (Ballard, 2003; Saguy & Dana, 2003).

Many factors are known to be effective in reducing fat uptake in fried food products. Other than oil characteristics, raw material properties, and product formulation, pre-processing factors like coating, blanching, drying, baking; processing factors such as oil temperature, use of vacuum and high pressure, and post-processing choices including cooling, shaking, microwave treatments are being manipulated to reduce fat uptake (Ziaiifar, et al., 2008). Among these methods coating of the products that are going to be fried provides some additional advantages to the manufacturers. Coating of foods may improve appearance, flavor and texture as well as weight and volume (Cunningham & Suderman, 1981; Fiszman & Salvador, 2003; Mohamed, et al., 1998). Batters and breading are like barriers that prevent moisture loss during cooking so a final product which is tender and juicy on the inside and crispy on the outside at the same time can be produced. Breading and battering can also limit fat uptake (Fiszman & Salvador, 2003).
Among processing conditions, frying temperature and applying high pressure during frying had been studied by many researchers. It is known that increasing frying temperature produces crispy fried foods with darker crust color. However, its effect on fat uptake is still not clear and contradictory results can be found in the literature (Ziaiifar, et al., 2008). Frying under high pressure can lower fat content of fried products while enabling higher moisture retention. Products fried under high pressure are found to be more tender and juicier than products fried at atmospheric pressure (Bengston, 2006; Innawong, 2001; P. Mallikarjunan, Chinnan, & Balasubramaniam, 1995; Rao, et al., 2005).

The main objective of this research was to study effects of frying temperature and pressure on breaded cheese stick quality. Moisture and fat contents, crispness, exterior and interior hardness, and color of the samples were selected as quality attributes.

3.3 Materials and Methods

3.3.1 Materials:

Commercially available par-fried frozen cheese sticks were obtained from Farm Rich, Rich Products Corporation (St. Simons Island, GA). The cheese sticks were packed and shipped with dry ice by the company. Upon arrival, they were stored in a freezer at -18°C in their original packages until testing. The frying oil was commercial soybean oil (Bakers & Chefs, North Arkansas Wholesale Company, Inc. Bentonville, AR).

3.3.2 Methods:

3.3.2.1 Frying Procedures:

Six pieces of par-fried frozen cheese sticks were fried in a modified pressure-fryer (Model 500C, Henny Penny, Inc., Eaton, OH) (Figure 3.2.). Three different temperatures (165
℃, 175 °C, and 185 °C) and three different pressure levels (101 kPa, 163 kPa, and 184 kPa) were used to fry the samples in approximately 24 L of oil. Cooking time for each temperature-pressure combination was chosen based on preliminary studies (Figure 3.1). Cooking was ended just before cheese blow-out occurred and after internal temperature, which was measured with a Type T thermocouple connected to a thermometer (Model HH21, Omega Engineering, Inc., Stamford, CT), reached 70 °C or above.

Innawong (2001) modified the fryer by replacing the exhaust tube with a tee. A universal connection was attached to the tee to allow compressed air used as a pressure source. Pressure levels of 163 kPa and 184 kPa were adjusted inside the fryer with the help of a safety relief connected to the operating valve, specific dead weights, and the fryer orifices. When 163 kPa and 184 kPa were used, there were 32 s and 40 s delays for opening the fryer, respectively.

Each combination was replicated four times. Nine combinations were completed in 3 days. Frying oil was filtered after every four experiments and fresh oil was added at the beginning of each day to keep the starting amount of oil at the same level and oil degradation at a minimum.

3.3.2.2 Color Analysis:

The color of the samples was measured by using a Minolta chromameter (Model CR-300, Minolta Camera Ltd, Osaka, Japan) calibrated to a white plate. CIE L, a, b parameters were recorded to characterize color of the crust of the fried cheese sticks. The test was replicated four times using three different samples. Eight measurements were taken from each sample.

3.3.2.3 Texture Analyses:

Crispness: A TA.XT2 texture analyzer with 50-kg load cell (Texture Technologies Corp, Scarsdale, NY; Stable Microsystems, Surrey, U.K.) was used to evaluate crispness of samples. A
five-bladed Kramer Shear unit was attached to the analyzer to record linear distance of the force curve, and number of positive peaks on the curve (Figure 3.3). One piece of cheese stick was placed at the bottom of the cell and tested at a test speed of 3 mm/s. The test was replicated 2 times using 3 different fried cheese sticks.

**Exterior and Interior Hardness:** In preliminary studies the average thickness of the crust of a fried cheese stick was found to be 4 mm. To evaluate exterior and interior hardness of cheese sticks, readings obtained from the texture analyzer were divided in 2 parts. The data coming from the first 4 mm of the force curve were associated with the exterior part of the sample and the rest of the data was used to explain how hard the interior part (melted cheese) was. Exterior and interior hardness of fried cheese sticks were measured with a craft knife blade. A craft knife blade (0.5 x 18 x 100 mm) was attached to a holder which was then attached to the texture analyzer (Figure 3.4). A single fried cheese stick was placed on the heavy duty platform of the analyzer and the craft knife cut the sample at a test speed of 3 mm/s until it reached 11 mm penetration depth. Maximum force within 4 mm of the force curve was recorded to determine exterior hardness of the samples while force value at penetration depth of 8 mm was measured to evaluate interior hardness of the samples. The test was replicated 2 times using 3 different fried cheese sticks.

**3.3.2.4 Moisture and Fat Content:**

Moisture and fat contents were measured for both the core and crust parts of the fried cheese sticks. The core and crust parts of the samples were separated with a razor blade, weighed and frozen immediately in a freezer at -18°C. Frozen samples were freeze-dried in a freeze dryer (The Virtis Company, Gardiner, NY) for 80 h. The masses of dried samples were weighed to determine moisture contents of fried cheese sticks. The test was replicated 4 times.
Fat contents of the fried cheese sticks were determined by using a Soxtec extraction unit and AOAC method 991.36 (AOAC, 2000). Petroleum ether was used as the solvent. The test was replicated 4 times.

3.3.2.5 Statistical Analysis:

The SAS statistical software package (version 9.2, 2008) was used to conduct a two-way analysis of variance and Fisher’s least significant difference (LSD) test to evaluate effects of pressure and temperature on color, crispness, exterior and interior hardness, moisture and fat contents of fried cheese sticks. Alpha (α) was set at 0.05 for all analyses.

3.4 Results and Discussions

The mean values of quality attributes for each frying pressure and temperature combination are reported in Table 3.1, 3.2, and 3.3. The p-values for the main effects (frying temperature and frying pressure) and interaction between frying temperature and pressure on the quality attributes are given in Table 3.4, 3.5, and 3.6. No significant interaction effect between frying temperature and pressure) was found.

3.4.1 Effects of Pressure and Temperature on Moisture Content

Pressure level had a significant (P<0.05) effect on crust moisture content. Samples fried at 163 kPa had significantly higher moisture content (26.22%) than samples fried at 101 and 184 kPa had (Table 3.7). Higher moisture contents in samples fried under high pressure were also observed by Mallikarjunan et al. (1995), Roa and Delaney (1995), and Innawong (2001). Frying under high pressure levels increased the boiling point of water which could increase moisture retention in crusts of the samples. On the other hand, there was no significant difference between 101 kPa and 184 kPa. The design of the fryer used in this research required samples to be dipped
in hot oil before high pressure applied. The delay for opening and closing the lid was 40 s when the samples were fried under 184 kPa. This meant that samples were not actually under 184 kPa for 40 s during frying. Samples fried at this pressure level were exposed to high pressure less than the samples fried under 163 kPa were. It was hypothesized that exposure time to high pressure of the samples fried under 184 kPa was not enough to make a significant difference.

Temperature had a significant (P<0.05) effect on crust moisture content. Samples fried at 175 °C and 185 °C did not show a significant difference in crust moisture content while they had significantly lower crust moisture contents than samples fried at 165 °C did (Table 3.8). As expected, moisture loss in the crust increased with increased temperature since the crust was in direct contact with the frying oil. Hubbard and Farkas (1999) found that increasing oil temperature enhanced heat transferred to the product which meant increased drying rates. Similar results were also obtained by other researchers. (Bengston, 2006; Budzaki & Seruga, 2004; Innawong, 2001; Sobukola, Awonorin, Oladimeji, & Olukayode, 2009).

Pressure level and temperature did not have any significant (P>0.05) effect on the core moisture (Table 3.7, Table 3.8). These results were contradictory to those found by Mallikarjunan et al. (1995), and Innawong (2001). The difference could be due to the different approaches taken to adjust the cooking time and exposure time to high pressure. Ending frying when the internal temperature of the samples was approximately 70 °C might have resulted similar moisture loss in the core part of the samples. Tangduangdee et al. (2003) also found that an increase of 10 °C in oil temperature, which was done in this research, did not have a significant effect on the center temperature of the samples.
3.4.2 Effects of Pressure and Temperature on Fat Content

Increasing pressure during frying did not change crust or core fat content of the samples significantly (P>0.05). These results were also contradictory to those found by Mallikarjunan et al. (1995), Innawong (2001), and Bengston (2006). Short exposure time to high pressure level could cause these findings. It can be seen in Table 3.9 that the mean values of 163 kPa and 184 kPa for crust fat content were lower than the mean value of 101 kPa but immersing the samples in hot oil before applying high pressure could have reduced the advantage of high pressure frying. Another important consideration was that relatively high initial fat content of breaded cheese stick. Unlike other products used in the studies by Innawong (2001) and Bengston (2006), breaded cheese had high contents of fat in the core which might have some interaction with fat uptake.

Increasing frying temperature significantly (P<0.05) changed crust fat content while it did not have any significant effect on core fat content (P>0.05). Crust fat content of samples fried at 175 °C was not significantly different than the crust fat contents of samples fried at 165 °C and 185 °C. On the other hand, samples fried at 185 °C had significantly lower crust fat contents than samples fried at 165 °C did (Table 3.10). Contradictions on the effect of frying temperature on fat content of fried products can be found in the literature. Gamble et al. (1987) reported a linear relationship between fat uptake and moisture loss. They also concluded that this relationship was not affected by frying temperature. Results found by Mallikarjunan et al. (1995), Moreira et al. (1995), Innawong (2001), and Sobukola et al. (2007) were in agreement with this theory. On the other hand, it was concluded that increasing frying temperature decreased frying time which let products be in touch with frying oil for shorter times and higher temperatures produced a fine, hard crust which could resist fat transfer by reducing diffusivity (Moyano & Berna, 2002).
Moyano and Pedreschi (2006), and Ziaiifar et al. (2009) found that increasing frying temperature decreased fat content.

Temperature increase did not change core fat content of the samples significantly (P>0.05) (Table 3.9 and 3.10). Both the breading nature of cheese sticks and approximately same internal temperature at the end of frying could have made no significant change in terms of core fat content.

3.4.3 Effects of Pressure and Temperature on Crispness

Pressure had a significant (P<0.05) effect on both linear distance of the force curve and number of positive peaks on the curve. Increasing pressure significantly decreased linear distance and number of the positive peaks. Linear distance of the force curve was found to be correlated well with the crispness of samples since a jagged curve would have higher linear distance value than a smooth curve which describes a less crispy product. Crispy samples would also produce jagged curves with many peaks (Varela, Salvador, & Fiszman, 2008). Samples fried at 101 kPa had higher linear distance and number of positive peak values than samples fried at 163 and 184 kPa which meant that frying at atmospheric pressure produced crispier samples than frying under high pressure (Table 3.11). The same observations were found by Mallikarjunan et al. (1995), Innawong (2001), and Bengston (2006), too. It was concluded that frying at atmospheric pressure produced a porous crust with open starch-protein network and less moisture content which made fried samples crispy (Rao, et al., 2005). However, Yusop et al. (2009) conducted a sensory test on chicken nuggets coated with wheat, rice, and sago flours and concluded that chicken nuggets fried under 156 kPa received higher crispness scores than chicken nuggets fried under 102 kPa.
Increasing frying temperature significantly ($P<0.05$) increased linear distance and number of positive peak values of the samples (Table 3.12). Both Innawong (2001) and Bengston (2006) reported that increasing temperature produced fried samples with dry, crispy crusts. Pedreschi and Moyano (2004) found that higher frying temperatures enhanced crust formation. Samples fried at 185 °C had lower crust and moisture contents than samples fried at 165 °C and 175 °C did and they were also found to be crispier than other samples. Varela et al. (2008) reported that moisture and fat contents and their distribution were related with crispness of fried products and reducing the amount of oil that can penetrate into the crust after frying could improve crispness of fried snacks (Vlieta, Vissera, & Luyten, 2007).

### 3.4.4 Effects of Pressure and Temperature on Exterior and Interior Hardness

Both temperature and pressure had significant ($P<0.05$) effects on exterior hardness of fried cheese sticks (Table 3.13, Table 3.14). Maximum force value within the first 4 mm of the force curve increased when temperature increased and pressure decreased. Same trend could also be seen in the crispness value of the samples and in the findings of Lima and Singh (2001), Innawong (2001), and Bengston (2006).

The force value at penetration depth of 8 mm was significantly ($P<0.05$) affected by frying temperature (Table 3.14). The force value increased as temperature increased. The effect of temperature was unexpected. One possible reason for this problem could be that the craft knife was in touch with the crust during cutting procedure. When the texture analyzer plotted force values against distance, all data was coming from the crust for the first 4 mm. After 4 mm, the craft knife started cutting both the core part and the crust. The crust had higher force values than the core part and this might have affected the readings since crust hardness increased with increased temperature.
Pressure level didn’t have any significant (P>0.05) effect on force value at penetration depth of 8 mm, which was also observed in preliminary studies (Table 3.13).

### 3.4.5 Effects of Pressure and Temperature on Color

The effects of pressure on L* and b* values were found significant (P<0.05). Samples fried at 163 kPa were darker and had higher b* value which indicated an increase in yellow color (Table 3.15). However, Innawong (2001) and Bengston (2006) found that frying under high pressure produced lighter products. Nonuniform color development and different particle sizes in breading could have caused this observation.

Temperature significantly (P<0.05) affected a* and b* values (Table 3.16). Increasing temperature increased a* and b* values. Increased a* and b* values indicated that samples fried at higher temperatures became redder and darker. Color development was dependent on Maillard reactions which were happening faster under high temperatures and producing darker colors (Garayo & Moreira, 2002).

### 3.5 Conclusions

Increasing pressure level to 163 kPa increased crust moisture content, b* value, decreased crispness and exterior hardness of breaded cheese sticks significantly (P<0.05). Pressure level did not have any significant effect on crust fat content of the samples (P>0.05). It was concluded that samples were not exposed to high pressure enough to reduce fat content due to the design of the fryer. The same problem could also explain why frying under 184 kPa wasn’t different than frying at 101 kPa in terms of product quality except crispness and exterior hardness. Increasing temperature decreased crust moisture and fat contents while it increased crispness and exterior hardness of the samples significantly (P<0.05).
3.6 References

Washington, DC.


Figure 3.1 Cooking time for each frying pressure and temperature combination
Table 3.1 The mean values of moisture and fat contents for every frying pressure and temperature combination

<table>
<thead>
<tr>
<th>Frying Pressure (kPa)</th>
<th>Frying Temperature (°C)</th>
<th>Crust Moisture Content (%)</th>
<th>Core Moisture Content (%)</th>
<th>Crust Fat Content (%)</th>
<th>Core Fat Content (%)</th>
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<tbody>
<tr>
<td>165</td>
<td>165</td>
<td>26.43</td>
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<td>19.18</td>
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Table 3.2: The mean values of number of positive peaks, linear distance, maximum force within 4mm, and force at penetration depth of 8 mm for every frying pressure and temperature combination

<table>
<thead>
<tr>
<th>Frying Pressure (kPa)</th>
<th>Frying Temperature (°C)</th>
<th>Number of Positive Peaks</th>
<th>Linear Distance (N.sec)</th>
<th>Maximum force within 4 mm (N)</th>
<th>Force at penetration depth of 8 mm (N)</th>
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</tr>
<tr>
<td>185</td>
<td>51.33</td>
<td>77.24</td>
<td>3.95</td>
<td>4.24</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.3 The mean values of L*, a*, and b* for every frying pressure and temperature combination

<table>
<thead>
<tr>
<th>Frying Pressure (kPa)</th>
<th>Frying Temperature (°C)</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>165</td>
<td>42.29</td>
<td>9.38</td>
<td>36.19</td>
</tr>
<tr>
<td>101</td>
<td>175</td>
<td>41.81</td>
<td>9.79</td>
<td>35.82</td>
</tr>
<tr>
<td></td>
<td>185</td>
<td>42.51</td>
<td>10.58</td>
<td>35.66</td>
</tr>
<tr>
<td>163</td>
<td>165</td>
<td>40.48</td>
<td>10.25</td>
<td>37.03</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>41.54</td>
<td>10.00</td>
<td>35.93</td>
</tr>
<tr>
<td></td>
<td>185</td>
<td>42.03</td>
<td>10.47</td>
<td>36.54</td>
</tr>
<tr>
<td>184</td>
<td>165</td>
<td>40.55</td>
<td>10.13</td>
<td>36.77</td>
</tr>
<tr>
<td></td>
<td>175</td>
<td>39.37</td>
<td>9.80</td>
<td>34.93</td>
</tr>
<tr>
<td></td>
<td>185</td>
<td>40.44</td>
<td>10.72</td>
<td>35.80</td>
</tr>
</tbody>
</table>
Table 3.4 The p-values for the main effects and interaction on moisture and fat contents

<table>
<thead>
<tr>
<th>Source</th>
<th>Crust Moisture Content</th>
<th>Core Moisture Content</th>
<th>Crust Fat Content</th>
<th>Core Fat Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frying Temperature</td>
<td>0.0040</td>
<td>0.7355</td>
<td>0.0203</td>
<td>0.5368</td>
</tr>
<tr>
<td>Frying Pressure</td>
<td>0.0161</td>
<td>0.1992</td>
<td>0.0964</td>
<td>0.0871</td>
</tr>
<tr>
<td>Frying Temperature x Frying Pressure</td>
<td>0.5818</td>
<td>0.5272</td>
<td>0.9019</td>
<td>0.4728</td>
</tr>
</tbody>
</table>
Table 3.5 The p-values for the main effects and interaction on number of positive peaks, linear distance, maximum force within 4 mm, and force at penetration depth of 8 mm

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of Positive Peaks</th>
<th>Linear Distance</th>
<th>Maximum Force within 4 mm</th>
<th>Force at penetration depth of 8 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frying Temperature</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.0123</td>
</tr>
<tr>
<td>Frying Pressure</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.0956</td>
</tr>
<tr>
<td>Frying Temperature x Frying Pressure</td>
<td>0.0988</td>
<td>0.7443</td>
<td>0.9531</td>
<td>0.7770</td>
</tr>
</tbody>
</table>
Table 3.6 The p-values for the main effects and interaction on L*, a*, and b*

<table>
<thead>
<tr>
<th>Source</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frying Temperature</td>
<td>0.1840</td>
<td>&lt;0.0001</td>
<td>0.0004</td>
</tr>
<tr>
<td>Frying Pressure</td>
<td>&lt;0.0001</td>
<td>0.1154</td>
<td>0.0256</td>
</tr>
<tr>
<td>Frying Temperature x Frying Pressure</td>
<td>0.2652</td>
<td>0.1330</td>
<td>0.2423</td>
</tr>
</tbody>
</table>
Table 3.7 Effect of pressure on crust and core moisture content

<table>
<thead>
<tr>
<th>Pressure level (kPA)</th>
<th>Crust moisture content (%)</th>
<th>Core moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>25.02&lt;sup&gt;b&lt;/sup&gt;</td>
<td>48.15&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>163</td>
<td>26.22&lt;sup&gt;a&lt;/sup&gt;</td>
<td>47.64&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>184</td>
<td>24.85&lt;sup&gt;b&lt;/sup&gt;</td>
<td>47.99&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 165, 175, and 185 °C. Means with different letter within a column are significantly different (P<0.05).
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Crust moisture content (%)</th>
<th>Core moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>165</td>
<td>26.32&lt;sup&gt;a&lt;/sup&gt;</td>
<td>48.02&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>175</td>
<td>25.20&lt;sup&gt;b&lt;/sup&gt;</td>
<td>47.95&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>185</td>
<td>24.57&lt;sup&gt;b&lt;/sup&gt;</td>
<td>47.80&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 101, 163, and 184 kPa. Means with different letter within a column are significantly different (P<0.05).
Table 3.9 Effect of pressure on crust and core fat content

<table>
<thead>
<tr>
<th>Pressure (kPA)</th>
<th>Crust fat content (%)</th>
<th>Core fat content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>20.52&lt;sup&gt;a&lt;/sup&gt;</td>
<td>17.14&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>163</td>
<td>19.59&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.44&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>184</td>
<td>19.78&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.15&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 165, 175, and 185 °C. Means with different letter within a column are significantly different (P<0.05).
Table 3.10 Effect of temperature on crust and core fat content

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Crust fat content (%)</th>
<th>Core fat content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>165</td>
<td>20.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>16.44&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>175</td>
<td>19.84&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>16.43&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>185</td>
<td>19.38&lt;sup&gt;b&lt;/sup&gt;</td>
<td>16.86&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 101, 163, and 184 kPa
Means with different letter within a column are significantly different (P<0.05).
Table 3.11 Effect of pressure on crispness

<table>
<thead>
<tr>
<th>Pressure (kPA)</th>
<th>Number of Positive peaks</th>
<th>Linear distance (N.sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>71.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>105.87&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>163</td>
<td>39.94&lt;sup&gt;b&lt;/sup&gt;</td>
<td>65.80&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>184</td>
<td>38.89&lt;sup&gt;b&lt;/sup&gt;</td>
<td>61.83&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 165, 175, and 185 °C
Means with different letter within a column are significantly different (P<0.05).
Table 3.12 Effect of temperature on crispness

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Number of Positive peaks</th>
<th>Linear distance (N.sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>165</td>
<td>38.28&lt;sup&gt;c&lt;/sup&gt;</td>
<td>62.29&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>175</td>
<td>51.44&lt;sup&gt;b&lt;/sup&gt;</td>
<td>76.55&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>185</td>
<td>60.78&lt;sup&gt;a&lt;/sup&gt;</td>
<td>94.67&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 101, 163, and 184 kPa. Means with different letter within a column are significantly different (P<0.05).
Table 3.13 Effect of pressure on exterior and interior hardness

<table>
<thead>
<tr>
<th>Pressure (kPA)</th>
<th>Maximum force within 4 mm (N)</th>
<th>Force at penetration depth of 8mm (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>4.55&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.67&lt;sup&gt;ab&lt;/sup&gt;</td>
</tr>
<tr>
<td>163</td>
<td>3.47&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4.46&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>184</td>
<td>2.74&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3.55&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 165, 175, and 185 °C. Means with different letter within a column are significantly different (P<0.05).
Table 3.14 Effect of temperature on exterior and interior hardness

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Maximum force within 4 mm (N)</th>
<th>Force at penetration depth of 8 mm (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>165</td>
<td>2.81^b</td>
<td>3.17^b</td>
</tr>
<tr>
<td>175</td>
<td>3.34^b</td>
<td>3.96^ab</td>
</tr>
<tr>
<td>185</td>
<td>4.61^a</td>
<td>4.55^a</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 101, 163, and 184 kPa
Means with different letter within a column are significantly different (P<0.05).
Table 3.15 Effect of pressure on color

<table>
<thead>
<tr>
<th>Pressure (kPA)</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>42.20</td>
<td>9.92</td>
<td>35.89</td>
</tr>
<tr>
<td>163</td>
<td>41.35</td>
<td>10.24</td>
<td>36.50</td>
</tr>
<tr>
<td>184</td>
<td>40.12</td>
<td>10.22</td>
<td>35.84</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 165, 175, and 185 °C. Means with different letter within a column are significantly different (P<0.05).
### Table 3.16 Effect of temperature on color

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Treatment means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L*</td>
</tr>
<tr>
<td>165</td>
<td>41.10(^a)</td>
</tr>
<tr>
<td>175</td>
<td>40.90(^a)</td>
</tr>
<tr>
<td>185</td>
<td>41.66(^b)</td>
</tr>
</tbody>
</table>

Each mean is the average of the responses of 101, 163, and 184 kPa.
Means with different letter within a column are significantly different (P<0.05).
Figure 3.2 Modified pressure fryer
Figure 3.3 Texture analyzer with Kramer Shear Blade
Figure 3.4 Custom made craft knife blade
CHAPTER 4:

Effects of Deep-fat Frying and Far-Infrared Cooking as Finish Cooking Methods on
Quality of Breaded Cheese Sticks

4.1 Abstract

Reducing fat content of fried foods to meet the demand of low-fat fried foods with high
quality by consumers can be accomplished in many ways. Infrared heating as a finish cooking
method has been used to produce foods with low fat content and acceptable quality attributes.
Effects of far-infrared cooking and deep-fat frying on the quality of par-fried frozen cheese sticks
were studied. Samples were deep-fat fried at 175 °C and finish cooked in a radiant oven at 480
°C, 505 °C, and 530 °C with and without brushing oil onto sample surfaces.

Far-infrared cooked samples had significantly (P<0.05) lower crust fat contents and
higher crust moisture contents than deep-fat fried samples had. However, crispness of far-
infrared cooked samples was lower than crispness of fried samples. Far-infrared cooking
significantly (P<0.05) increased a* and b* values.

Keywords: deep-fat frying, far-infrared cooking, fat content, crispness
4.2 Introduction

Deep-fat frying is a very common cooking method since fried foods are demanded by consumers because of their organoleptic properties (Mir-Bel, et al., 2009). A large variety of foods, such as, potato, chicken nuggets, fish sticks, doughnuts, are deep-fat fried. One of the main characteristics of fried foods is a crispy, porous, and oily crust and a moist cooked core (Bouchon, et al., 2001).

Fried foods may have fat contents up to 1/3 of their total weight. Besides desirable attributes, fried products are considered to be unhealthy due to their high fat contents (Mellama, 2003). Increasing demand for healthy food products having high quality has resulted in a demand to produce low-fat fried foods along with acceptable quality attributes (Ballard, 2003).

Fat uptake in fried food products can be limited in different ways. During the pre-processing step, coating, blanching, or drying could be applied (Ziaiifar, et al., 2008). Among these methods, coating of food materials has been used for all types of foods and it was proven to improve quality characteristics (Cunningham & Suderman, 1981; Fiszman & Salvador, 2003; Mohamed, et al., 1998). Coating applications can also limit fat uptake and prevent moisture loss during frying resulted in a fried product that is juicy on the inside and crispy on the outside (Fiszman & Salvador, 2003).

Many patented works have been done to reduce fat uptake in the post-frying step by using combinations of different heat treatments such as microwave heating, superheated steam, and infrared radiation (August, 1991; Chujin, Shukukei, Heiki, & Isho, 2001; Fosb, et al., 1998; Masaki, 2006). Lloyd et al. (2004) showed that par-fried frozen French fries which were cooked in a radiant heating oven had consistent texture, color, and consumer acceptability compared to deep-fat fried samples. Melito (2009) used a similar radiant oven to finish cook partially fried
donuts. It was concluded that donuts that were finish cooked in the radiant oven had lower fat contents than deep-fat fried ones and still had with acceptable quality.

Far-infrared heating of foods has many applications. Some of the applications are baking, roasting, drying, thawing, pasteurization, and sterilization. Far-infrared heating of foods is considered to be a very efficient method since no heating medium such as hot air or oil is required to supply heat to the foods and absorptivity of most food substances is higher at the far-infrared region (Sakai & Hanzawa, 1994).

The objectives of this study were to use traditional deep-fat frying method and far-infrared cooking to finish cook par-fried frozen cheese sticks and compare these methods in terms of moisture and fat contents, crispness, exterior and interior hardness, and color of the samples.

4.3 Materials and Methods

4.3.1 Materials:

Commercially available par-fried frozen cheese sticks were obtained from Farm Rich, Rich Products Corporation (St. Simons Island, GA). The cheese sticks were packed and shipped with dry ice by the company. Upon arrival, they were stored in a freezer at -18°C in their original packages until testing. The frying oil was commercial soybean oil (Bakers & Chefs, North Arkansas Wholesale Company, Inc. Bentonville, AR).

4.3.2 Methods:

4.3.2.1 Cooking Procedures:

Six pieces of par-fried frozen cheese sticks were finish cooked in three different ways. In the first way, samples were deep-fat fried in a modified pressure-fryer (Model 500C, Henny Penny, Inc., Eaton, OH). In the other two ways, a modified radiant oven (XWAV 1417, APW...
Wyott, Dallas, TX) was used to cook samples with far-infrared radiation (Figure 4.1). The radiant oven had five ceramic heaters (Salamander Ceramic Heater FTE-500, Mor Electric Heating Assoc., Inc., Comstock Park, MI) on top and a metal sheathed element which was not used in this study at the bottom. The dimensions of the cooking chamber were 56.50 cm x 38.45 cm x 23.70 cm. Inner surfaces of the cooking chamber were covered with aluminum foil to increase reflection of infrared radiation onto samples. A PID controller (Eurotherm 2132, Process Engineering Products Company, Inc., Richmond, VA) was used to control temperature of ceramic heaters.

Two different procedures were followed to cook the samples in the radiant oven. In the first procedure, surface temperatures of the ceramic heaters were set at 480 °C, 505 °C, and 530 °C to cook frozen par-fried breaded cheese sticks. In the second procedure, to decrease reflectivity on the sample surface and increase the amount of radiant energy that could be absorbed by samples, soybean oil (Bakers & Chefs, North Arkansas Wholesale Company, Inc., Bentonville, AR) was applied onto sample surfaces with a food brush. In both procedures, samples were placed on a cooling wire to let the samples receive infrared radiation from the bottom side as well. The distance between the cooling wire and ceramic heaters was 10 cm. Heat flux emitted by the ceramic heaters at the given temperatures was measured using the method described by Staack et al. (2008). A black-painted aluminum block (83 mm x 26 mm x 14 mm) with a type K thermocouple in the center was used (Figure 4.2).

Cooking time for each heating treatment was chosen based on preliminary studies (Table 4.1). Cooking was ended just before cheese blow-out occurred and after the internal temperature, which was measured with a Type T thermocouple connected to a thermometer.
(Model HH21, Omega Engineering, Inc., Stamford, CT), reached 70 °C or above. During far-infrared cooking, samples were flipped over halfway through cooking time.

4.3.2.2 Color Analysis:

The color of the samples was measured with a Minolta chromameter (Model CR-300, Minolta Camera Ltd, Osaka, Japan) calibrated to a white plate. CIE L, a, b parameters were recorded to characterize the color of the crust of the cooked cheese sticks. The test was replicated four times using three different samples. Eight measurements were taken from each sample.

4.3.2.3 Texture Analyses:

Crispness: A TA.XT2 texture analyzer with a 50-kg load cell (Texture Technologies Corp, Scarsdale, NY; Stable Microsystems, Surrey, U.K.) was used to evaluate crispness of samples. A five-bladed Kramer Shear unit attached was used to the analyzer to record linear distance of the force curve, and number of positive peaks on the curve. One piece of cheese stick was placed at the bottom of the cell and tested at a test speed of 3 mm/s. The test was run 2, 3, and 4 min after cooking and replicated 2 times.

Exterior and Interior Hardness: A custom-made stainless steel probe with 3-mm diameter was used to measure exterior and interior hardness of cooked cheese sticks (Figure 4.3). To evaluate exterior and interior hardness of cheese sticks, readings obtained from the texture analyzer were divided in 2 parts. The data coming from the first 4 mm of the force curve was associated with the exterior part of the sample and the rest of the data was used to explain how hard the interior part (melted cheese) was. A single fried cheese stick was placed on the heavy duty platform of the analyzer and tested with the puncture probe at a test speed of 3 mm/s. Penetration depth was 14 mm. Maximum force within 4 mm of the force curve was recorded to determine exterior hardness of the samples while the force value at penetration depth of 10 mm was measured to
evaluate interior hardness of the samples. The test was conducted 2, 3 and, 4 min after frying and replicated 2 times.

4.3.2.4 Moisture and Fat Content:

Moisture and fat contents were measured for both the core and crust parts of the fried cheese sticks. The core and crust parts of the samples were separated with a razor blade, weighed and frozen immediately in a freezer at -18°C. Frozen samples were freeze-dried in a freeze dryer (The Virtis Company, Gardiner, NY) for 80 h. The masses of dried samples were weighed to determine moisture contents of fried cheese sticks. The test was replicated 4 times.

Fat contents of the fried cheese sticks were determined by using a Soxtec extraction unit and AOAC method 991.36 (AOAC, 2000). Petroleum ether was used as the solvent. The test was replicated 4 times.

4.3.2.5 Statistical Analysis:

One-way analysis of variance and Fisher’s least significant difference (LSD) test were performed to evaluate effects of cooking methods on color, crispness, exterior and interior hardness, moisture and fat contents of fried cheese sticks by using The SAS statistical software package (version 9.2, 2008). Alpha (α) was set at 0.05 for all analyses.

4.4 Results and Discussion

Brushing soybean oil onto sample surfaces before far-infrared cooking caused an average of 1.15 ± 0.13 % increase in sample weight. Heat fluxes for 480 °C, 505 °C, 530 °C were 8.64 kW/ m², 11.73 kW/m², and 17.31 kW/m², respectively.
4.4.1 Effects of Finish Cooking Methods on Moisture Content

Finish cooking method significantly (P<0.05) affected crust moisture content of the samples. Samples cooked with far infrared radiation had higher moisture contents than deep-fat fried samples had (Table 4.2). Hubbard and Farkas (1999) reported a maximum heat flux of 23,900 W/m² during frying of potato slices at 180 °C. Although this heat flux value was reported for a potato product, it might be assumed that heat flux value during frying of breaded cheese sticks would be close to this reported value and higher than the heat flux values of far-infrared cooking. This possible difference could be the reason of higher moisture retention in the samples cooked with far-infrared radiation. Higher moisture retention in par-fried infrared finished donuts than fully fried donuts was found by Melito (2009). Among the samples cooked with far-infrared radiation, samples brushed with oil except the one cooked at 530 °C had lower crust moisture contents than others. This could be due to the fact that applying oil onto sample surfaces increased absorptivity of the samples which in return, increased drying rate. Increased drying rate with an increase in heat flux was also observed by Hubbard and Farkas (1999).

Different finish cooking methods did not any significant (P>0.05) effect on core moisture contents of the samples (Table 4.2). Cooking the samples to approximately the same core temperature and low penetration depth of far-infrared radiation could explain this observation.

4.4.2 Effects of Finish Cooking Methods on Fat Content

As expected, crust fat contents of samples cooked with far-infrared radiation were significantly (P<0.05) lower than crust fat content of fried samples. The reduction in crust fat content was between 20.17% and 29.83%. Breaded cheese sticks cooked at 480 °C with oil
brushing had higher crust fat content (16.27%) than other far-infrared finished cooked samples had (Table 4.3). The lowest crust fat content (14.30%) belonged to the samples cooked at 505 °C without oil brushing. Excluding the samples cooked at 530 °C without oil brushing, increasing surface temperature of ceramic heaters and heat flux decreased crust fat content of the samples. Melito (2009) reported similar results and concluded that increasing heat flux might have decreased the viscosity of oil on the sample surface and allow the oil to drip off of the sample easily.

Cooking method did not change core fat content of the samples significantly (P>0.05). Possible reasons for this result could be low penetration depth of far-infrared radiation and same core temperature at the end of cooking.

**4.4.3 Effects of Cooking Methods on Crispness**

Both number of positive peaks and linear distance were significantly (P<0.05) affected by cooking methods. Deep-fat fried samples had the highest values for number of positive peaks and linear distance which indicated that they were crispier than samples cooked with far-infrared radiation (Table 4.4). Low heat fluxes during infrared cooking could result in low crispness of the samples. Penetration depth of far-infrared radiation was reported to be very little, and for drying applications, it was found that foods with thickness greater than the penetration depth could not be dried evenly by far-infrared radiation (Das, Das, & Bal, 2004; Hebbar, Vishwanathan, & Ramesh, 2004; Sakai & Hanzawa, 1994). During far-infrared cooking of breaded cheese sticks, moisture removal from the crust part of the samples started but the moisture migration from inner parts to the sample surface was also triggered. Due to low heat flux and penetration depth, this moisture migration could have eventually made the samples soggy and less crispy than fried breaded cheese sticks.
Increasing surface temperature, which meant increased heat flux, and brushing oil onto samples increased linear distance and number of positive peaks of the samples (Table 4.4). However, this increase showed different trends for the measurements taken. While samples brushed with oil had higher number of positive peaks than all the other far-infrared cooked samples, samples brushed with oil had higher linear distance than only the samples cooked at the same temperature.

4.4.4 Effects of Cooking Methods on Exterior and Interior Hardness

Cooking method significantly (P<0.05) affected exterior hardness of the samples. Deep-fat frying resulted in higher force values within the first 4 mm than far infrared cooking had (Table 4.5). Low drying rate during far-infrared cooking could be the reason why crust moisture contents of far infrared cooked samples were higher. Breaded cheese sticks cooked at 530 °C without oil brushing had higher exterior hardness than other infrared cooked samples but it was only statistically different than samples cooked at 480 °C with oil brushing. The standard deviation of maximum force within 4 mm was between 29 and 56% for samples cooked with far-infrared radiation which made the data less reliable in attempting to explain the effects. When a puncture probe was used, high standard deviation was observed by other researchers (Lloyd, et al., 2004; Walter, Truong, & Espinel, 2002), too. Non uniform crust formation caused by cooking methods and coating of samples could be the reason for this high standard deviation.

The force value at penetration depth of 10 mm, which was used as an indicator of interior hardness, was not affected significantly (P<0.05) by cooking method. Cooking samples until approximately the same internal temperature may have caused the core part (melted cheese) to have the same hardness for every combination. A puncture probe might be used to measure interior hardness of breaded cheese sticks.
4.4.5 Effects of Cooking Methods on Color

Effects of cooking methods on L*, a*, and b* values were found significant (P<0.05). Samples cooked at 480 °C without oil brushing had the highest L* and b* values among all the other samples (Table 4.6). The L* value of deep-fat fried samples was significantly (P<0.05) higher than only L* value of samples cooked at 480 °C with oil brushing. The a* and b* values of far-infrared cooked samples were significantly (P<0.05) higher than deep-fat fried samples. The effects of increased temperature and oil brushing were not clear. Different particle sizes in breading material and color measurement method, which depended on measurement location, could be the possible reasons for that outcome.

4.5 Conclusions

Crust fat content of far-infrared cooked frozen par-fried breaded cheese sticks with and without oil brushing was lower than crust fat content of deep-fat fried samples. Moisture retention in far-infrared cooked samples was higher than in deep-fat fried samples. The drawback of far-infrared cooking was that samples cooked with this method were less crispy than deep-fat fried samples. Brushing oil onto the sample surfaces before infrared cooking increased crispness of samples but it was still not enough to reach crispness values of fried samples. While L* values of far-infrared cooked samples were lower than those of fried samples, a* and b* values were significantly higher than the values of deep-fat fried samples. Puncture probe was not found suitable for measuring exterior hardness of breaded cheese sticks, but it gave reliable results for interior hardness.
4.6 References


Washington, DC.


Table 4.1 Cooking time for finish cooking methods

<table>
<thead>
<tr>
<th>Cooking method</th>
<th>Cooking time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-fat frying</td>
<td>150</td>
</tr>
<tr>
<td>Far infrared cooking at 480 °C without oil brushing (FIR 480 – w/o oil)</td>
<td>235</td>
</tr>
<tr>
<td>Far infrared cooking at 505 °C without oil brushing (FIR 505 – w/o oil)</td>
<td>225</td>
</tr>
<tr>
<td>Far infrared cooking at 530 °C without oil brushing (FIR 530 – w/o oil)</td>
<td>205</td>
</tr>
<tr>
<td>Far infrared cooking at 480 °C with oil brushing (FIR 480 – with oil)</td>
<td>210</td>
</tr>
<tr>
<td>Far infrared cooking at 505 °C with oil brushing (FIR 505 – with oil)</td>
<td>190</td>
</tr>
<tr>
<td>Far infrared cooking at 530 °C with oil brushing (FIR 530 – with oil)</td>
<td>185</td>
</tr>
</tbody>
</table>
### Table 4.2 Effect of cooking method on crust and core moisture content

<table>
<thead>
<tr>
<th>Cooking Method</th>
<th>Crust moisture content (%)</th>
<th>Core moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-fat frying</td>
<td>24.71&lt;sup&gt;b&lt;/sup&gt;</td>
<td>48.02&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 480-w/o oil</td>
<td>29.89&lt;sup&gt;a&lt;/sup&gt;</td>
<td>48.19&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 505-w/o oil</td>
<td>29.38&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>48.00&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 530-w/o oil</td>
<td>28.49&lt;sup&gt;b&lt;/sup&gt;</td>
<td>48.10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 480-with oil</td>
<td>29.21&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>48.28&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 505-with oil</td>
<td>29.13&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>48.41&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 530-with oil</td>
<td>28.66&lt;sup&gt;b&lt;/sup&gt;</td>
<td>48.44&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Means with different letter within a column are significantly different (P<0.05).
<table>
<thead>
<tr>
<th>Cooking Method</th>
<th>Crust fat content (%)</th>
<th>Core fat content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-fat frying</td>
<td>20.38&lt;sup&gt;a&lt;/sup&gt;</td>
<td>17.24&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 480-w/o oil</td>
<td>14.69&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>16.54&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 505-w/o oil</td>
<td>14.30&lt;sup&gt;c&lt;/sup&gt;</td>
<td>16.23&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 530-w/o oil</td>
<td>14.75&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>16.77&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 480-with oil</td>
<td>16.27&lt;sup&gt;b&lt;/sup&gt;</td>
<td>15.98&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 505-with oil</td>
<td>16.10&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>15.79&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 530-with oil</td>
<td>15.41&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>16.55&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Means with different letter within a column are significantly different (P<0.05).
Table 4.4 Effect of cooking method on crispness

<table>
<thead>
<tr>
<th>Cooking Method</th>
<th>Number of positive peaks</th>
<th>Linear distance (N.sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-fat frying</td>
<td>75.83 \textsuperscript{a}</td>
<td>128.32 \textsuperscript{a}</td>
</tr>
<tr>
<td>FIR 480-w/o oil</td>
<td>36.00 \textsuperscript{c}</td>
<td>55.28 \textsuperscript{b}</td>
</tr>
<tr>
<td>FIR 505-w/o oil</td>
<td>37.17 \textsuperscript{c}</td>
<td>57.57 \textsuperscript{b}</td>
</tr>
<tr>
<td>FIR 530-w/o oil</td>
<td>40.17 \textsuperscript{bc}</td>
<td>60.98 \textsuperscript{b}</td>
</tr>
<tr>
<td>FIR 480-with oil</td>
<td>40.50 \textsuperscript{bc}</td>
<td>57.39 \textsuperscript{b}</td>
</tr>
<tr>
<td>FIR 505-with oil</td>
<td>44.67 \textsuperscript{bc}</td>
<td>60.29 \textsuperscript{b}</td>
</tr>
<tr>
<td>FIR 530-with oil</td>
<td>50.67 \textsuperscript{bc}</td>
<td>68.29 \textsuperscript{a}</td>
</tr>
</tbody>
</table>

Means with different letter within a column are significantly different (P<0.05).
Table 4.5 Effect of cooking method on exterior and interior hardness

<table>
<thead>
<tr>
<th>Cooking Method</th>
<th>Maximum force within 4 mm (N)</th>
<th>Force at penetration depth of 10 mm (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-fat frying</td>
<td>6.66&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.24&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 480-w/o oil</td>
<td>1.87&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.21&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 505-w/o oil</td>
<td>2.39&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.22&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 530-w/o oil</td>
<td>2.70&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.22&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 480-with oil</td>
<td>1.28&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.34&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 505-with oil</td>
<td>2.35&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.28&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FIR 530-with oil</td>
<td>2.20&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>0.31&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Means with different letter within a column are significantly different (P<0.05).
<table>
<thead>
<tr>
<th>Cooking Method</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep-fat frying</td>
<td>41.87</td>
<td>9.71</td>
<td>35.79</td>
</tr>
<tr>
<td>FIR 480-w/o oil</td>
<td>43.54</td>
<td>11.41</td>
<td>38.46</td>
</tr>
<tr>
<td>FIR 505-w/o oil</td>
<td>41.57</td>
<td>12.00</td>
<td>37.78</td>
</tr>
<tr>
<td>FIR 530-w/o oil</td>
<td>41.14</td>
<td>12.25</td>
<td>37.70</td>
</tr>
<tr>
<td>FIR 480-with oil</td>
<td>40.45</td>
<td>12.21</td>
<td>37.53</td>
</tr>
<tr>
<td>FIR 505-with oil</td>
<td>41.79</td>
<td>11.95</td>
<td>38.39</td>
</tr>
<tr>
<td>FIR 530-with oil</td>
<td>40.94</td>
<td>12.46</td>
<td>37.91</td>
</tr>
</tbody>
</table>

Means with different letter within a column are significantly different (P<0.05).
Figure 4.1 Modified radiant oven used in this study
Figure 4.2 Black painted aluminum block used to measure heat flux inside the radiant oven
Figure 4.3 Custom made puncture probe attached to the texture analyzer
CHAPTER 5:
Summary and Conclusions

This study investigated the suitability of different frying factors (frying temperature and frying pressure) and a far infrared finish cooking method for limiting fat uptake in par fried frozen breaded cheese sticks. Moisture and fat contents of crust and core parts, crust color, crispness, exterior and interior hardness of the samples were measured in order to evaluate effects of frying temperature, frying pressure and far infrared finish cooking method. The study was completed in two parts.

In the first part, three frying temperatures (165 °C, 175 °C, 185 °C) and three frying pressure levels (101 kPa, 163 kPa, 184 kPa) were used to fry breaded cheese sticks. Frying time for each temperature-pressure combination was determined in preliminary studies. Frying was ended right before cheese blow-out occurred and after internal temperature reached 70 °C or above. Increasing frying temperature significantly (P<0.05) reduced crust fat content and crust moisture content while crispness and exterior hardness were increased with increasing temperature. a* and b* values were higher for the samples fried at higher temperatures which indicated color development was accelerated and samples became darker and redder. Pressure did not affect crust fat content significantly (P>0.05). Breaded cheese sticks fried under high pressure had higher crust moisture contents than cheese sticks fried at 101 kPa (atmospheric level) did (P<0.05). Increasing pressure reduced crispness and exterior hardness of the samples while L* and b* values were increased. Neither core moisture content nor core fat content was affected by frying pressure and temperature. Interior hardness of breaded cheese sticks was measured with a custom made craft knife blade but the results were unexpected.
In the second part, par fried frozen breaded cheese sticks were finish cooked in a modified radiant oven and compared to the deep-fat fried samples in terms of crust and core fat/moisture contents, crispness, exterior and interior hardness, and color. Ceramic heaters of the oven were set to three temperatures (480 °C, 505 °C, 530 °C) for cooking. Two different procedures were used to finish cook frozen breaded cheese sticks. In the first procedure, frozen cheese sticks were transferred to the radiant oven and cooked. In the second part, frozen cheese sticks were brushed with soybean oil to increase the amount of radiant energy that can be absorbed and decrease reflectivity of radiation. As expected, crust fat contents of far infrared finish cooked samples were significantly (P<0.05) lower than those of deep-fat fried samples. Moisture loss was lower in far infrared cooked samples which resulted in higher crust moisture contents. Far infrared finish cooking significantly reduced crispness and exterior hardness of breaded cheese sticks. Mean values of crispness for samples brushed with oil were higher than other far infrared finish cooked samples but the procedure was not good enough to produce samples as crispy as fried ones. Color of the far infrared cooked samples was darker than color of deep-fat fried samples.

For the first part of this research, it was concluded that breaded cheese sticks were not exposed to high pressure for enough time due to the equipment available. First, samples were immersed into frying oil and then high pressure was applied. This procedure could have reduced the advantageous of pressure frying. On the other hand, breaded cheese sticks are more sensitive products than chicken nuggets or fish sticks which were used in previous studies. Unlike other products, breaded cheese sticks are also relatively high in fat content. This initial fat content might have some interaction with fat uptake mechanism. Changing fryer design to a system which enables the usage of different exposure time is recommended. Breaded cheese sticks with
different initial fat contents can be prepared and an interaction between initial fat content and fat uptake mechanism of deep-fat fried samples may be investigated in future studies.

For further studies of the second part, a radiant oven capable of reaching higher temperatures and heat fluxes should be used. Far infrared cooking can also be combined with hot air drying to reduce crust moisture content which in return may increase crispness of food products. Radiative properties of frozen par fried cheese sticks could be determined to design a selective infrared cooking system. Edible films limiting moisture transfer from core part to crust can be used to increase crispness.