The Effect of Novel Frying Methods on Quality of Breaded Fried Foods

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ABSTRACT

Fried foods are popular around the world. They are also high in fat and considered unhealthy by many people. Reducing the fat content of fried food may allow for even more growth in their popularity, while allowing for healthier eating. Furthermore, vacuum-frying and frying with nitrogen gas have both been shown to extend the life of frying oil.

In this study, the use of novel frying methods as a way to reduce fat content of breaded fried foods was evaluated. A pressure fryer was modified so that fish sticks could be vacuum-fried and fried using external gas (nitrogen and compressed air) as the pressurizing media. These products were compared to those pressure fried and fried atmospherically in terms of crust color, moisture content, oil content, texture, and juiciness.

Overall, products fried using nitrogen and air were not found to be significantly different ($p < 0.05$) from each other. These products were both more tender and lower in oil content than steam-fried fish sticks. The energy to peak load of fish sticks fried with air was 123.10 J/kg, fish sticks fried with nitrogen had an energy to peak load of 134.64 J/kg, and fish sticks fried with traditional pressure frying had a peak load of 158.97 J/kg. The crust oil contents of fish sticks fried with air, nitrogen, and steam were 17.35%, 15.88%, and 23.31% oil by weight, respectively. In other words, using nitrogen or air to fry fish sticks reduced the fat uptake in the crust by 31.8% and 25.6% compared to traditional pressure frying, respectively.

The only area where vacuum-frying had a significant effect, when compared to pressure-fried and atmospherically-fried fish sticks, was in juiciness. Vacuum-frying created significantly juicier fish sticks than the other two frying methods. Vacuum-fried fish sticks had juiciness of 43.03% (120°C) and 41.31% (150°C), while pressure-fried fish sticks had juiciness of 30.01% (175°C) and 32.93% (190°C), and atmospherically-fried fish sticks had juiciness of 31.56% (175°C) and 29.38% (190°C). In addition, vacuum-fried fish sticks were more tender than atmospherically-fried fish sticks.

This results of this study demonstrated that frying with external pressurizing media can be used to reduce oil content in fish sticks, while also creating products that are more tender than conventionally pressure-fried fish sticks. In addition, vacuum-frying, which has been shown to extend oil life compared to pressure frying because of the lower temperatures involved, can be used to create fish sticks that are comparable to pressure-fried fish sticks, but juicier.

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CHAPTER 1

INTRODUCTION

Fried foods are tasty and popular around the world. One of the main reasons for this popularity is the “textural dichotomy of the food: dry and crispy crust, tender inside” (Mellema, 2003). Unfortunately, fried foods are also high in fat, in some cases reaching 1/3 of the total food product by weight (Mellema, 2003). The development of low-caloric food products with reduced fat and cholesterol levels has become very important in research and industry (Ang, 1993). Medical findings that correlate high intake of fat and cholesterol to arterial and heart disease (American Heart Association, 1986) have pushed this trend.

Food products fried via pressure frying are more juicy and tender than foods fried at atmospheric pressure (Innawong, 2001). Currently, pressure fryers depend on the steam released from large food loads to generate pressure inside the fryer (Innawong, 2001), which can lead to wasted food products in commercial applications. Using nitrogen gas as the pressurizing medium during frying has been shown to give food products of equal or better quality than traditional pressure frying. In addition, the oil life was greatly extended (Innawong, 2001).

Vacuum frying occurs at pressures well below atmospheric levels. It has been used for some time in the frying of fruit chips (Minelli and Harney, 2000). Recently, Garayo and Moreira (2002) demonstrated the reduction of fat in potato chips caused by frying under vacuum conditions as opposed to atmospheric conditions.

During frying, oil quality is greatly reduced. The oil is hydrolyzed and oxidized, forming free fatty acids and polar compounds. Steam released by food products during pressure frying greatly increases the degradation. When nitrogen gas is used to generate the pressure for frying, oil life can be extended (Innawong, 2001). During vacuum frying, oil life and quality are increased because the low temperatures and pressures reduce deterioration and oxidation of the frying oil (Imai, 1989).

Hypothesis

The hypothesis of this research is that there will not be a significant difference between the use of air and nitrogen as pressure mediums during deep-fat frying. In addition, frying with air and nitrogen will give similar or better quality fried foods when compared to pressure frying. Finally, vacuum frying will create fried foods with reduced oil content when compared to pressure or atmospheric frying.

Objectives

The goal of this research was to determine the effect of novel frying methods, frying using nitrogen gas and air as the pressurizing mediums and vacuum frying, on a breaded fried seafood product. The specific objectives were as follows:

1. Develop a vacuum fryer for use with breaded fried foods.
2. Determine the effects of frying with nitrogen, frying with air, and vacuum frying on the quality of a breaded fried food, specifically fish sticks, in terms of moisture and oil content, juiciness, color, and texture.

Rationale and Significance

Americans are becoming more concerned with their diets and overall fat intake. The American government is also making great strides to address the issue of obesity and poor eating habits among Americans. However, fried foods are still tasty and popular around the country. The creation of a process to create delicious low-fat breaded fried foods would benefit both the food industry and consumers. This research was performed to elucidate the possibility of such a process.

CHAPTER 2

LITERATURE REVIEW

The most popular foods in the industry are produced through frying. This is a complicated method for cooking involving many different simultaneous processes. Although popular, they have a perception of being unhealthy. This review will provide information about the frying process, issues related to frying, and the current research on frying.

2.1 Frying Process

During the frying process, water evaporates from inside the product being fried, creating voids that are penetrated by the oil. As long as there is moisture to evaporate, the product will stay at a temperature of roughly 100^{o}C (Blumenthal, 1996). As the water evaporates, the crust indicative of fried foods is formed on the exterior of the product.

There are three simultaneous processes occurring: heat transfer from the hot oil to the product, mass transfer of the water from the interior of the product to the exterior and then into the oil, and mass transfer of the oil into the product. Because of the high temperatures and the presence of water vapor (steam), the oil is also undergoing chemical changes.

2.1.1 Heat Transfer

There is a rapid rise in the surface temperature of a food placed in hot oil. As the product's internal moisture is vaporized into steam, the surface begins to dry. A crunchy crust forms on the outside as the plane of evaporation moves inside the food (Fellows, 2000) and hot fat begins to penetrate the food. The crust prevents large amounts of fat from passing through to the inside of the product (Moreiras-Varelo *et al*., 1988). A film of oil surrounds the product upon removal from the fryer. The thickness of this film controls the rate of heat and mass transfer. The viscosity and velocity of oil determine the thickness of this boundary layer (Fellows, 2000).

The initial mechanism considered for oil uptake was the condensation mechanism. Although there is no direct proof of this mechanism, it's been composed using common sense. According to the condensation mechanism for oil uptake, as vapor escapes foods frying in hot oil, an overpressure is created inside the food's pores. This prevents the oil from penetrating the food. This "barrier of escaping steam" continues until just after the food is removed from the oil (Mellema, 2003). As the food cools, the vapor inside the crust condenses, creating an underpressure in the pores. The film of oil surrounding the food product is driven into the pores by the underpressure (Mellema, 2003). Because there is no evidence to support this theory, it has largely been replaced by the capillary mechanism of oil uptake, which is based on fluid flow through porous media.

After frying, according to the capillary mechanism, the pores of a food are filled with vapor. During cooling, the surface tension between the thin film of frying oil surrounding the product and the vapor inside the pores increases as the temperature decreases. The capillary pressure, or pressure difference between two immiscible fluids (in this case, water vapor and oil), subsequently increases, causing the surface oil to enter the pores (Moreira *et al*., 1999). The hot oil fills the larger capillaries first, because water vapor is removed from them first (Fellows, 2000). This mechanism has experimental evidence to support it (Saguy and Pinthus, 1995; Moreira and Barrufet, 1998).

There is both convective and conductive heat transfer during frying. The convection occurs between the hot oil and the food, while conduction occurs within the product being fried (Singh, 1995). The rate of convective heat transfer depends on the temperature difference between the oil and the food and by the product surface heat transfer coefficient (Fellows, 2000). Water vapor bubbles escaping from the food also affect the transfer of heat from the oil to the food (Singh, 1995). The rate of conductive heat transfer depends on the thermal properties of the food, such as specific heat, thermal conductivity, and thermal diffusivity. To complicate matters, these properties will change with temperature during the frying process (Singh, 1995).

Farkas *et al*. (1996) have suggested that the frying process can be divided into four stages: initial heating, surface boiling, falling rate, and bubble end-point. During the initial heating stage, which usually only lasts a few seconds, the food surface is heated to the elevated boiling point of water (approximately 103^{o}C) through natural heat convection. There is no vaporization of water from the surface of the food during this short time. When vaporization begins, so does the surface boiling stage. The mode of heat transfer changes to forced convection, because of the turbulence in the surrounding oil caused by escaping water vapor. The crust begins to form at the surface of the food during this stage. The falling rate stage is similar to the falling rate period that takes place during food dehydration processes. This is when more internal moisture leaves the food and the internal core temperature rises to the boiling point. The internal core region is undergoing several physicochemical changes, such as cooking and starch gelatinization, and the crust layer is increasing in thickness. After sufficient time, the vapor transfer to the surface decreases. If the food is fried for a considerably long period of time, the bubble end point will be reached. At this final stage, the rate of moisture removal diminishes and no more bubbles are seen escaping the food surface. The crust layer continues to increase in thickness as the frying process proceeds.

2.1.2 Reduction of Fat Uptake

There are three basic routes for the reduction of fat uptake – modification of frying techniques, edible coatings and batters, and modification of frying medium.

2.1.2.1 Modification of Frying Techniques

It has been shown that the conditions following the removal of food from the fryer are very important in terms of fat uptake. Proper shaking and draining of the food can help reduce fat content, as can frying for the proper duration at the correct temperature (Mellema, 2003). Further research has been done on how the actual frying process can be modified to reduce oil uptake. Some researchers (Innawong *et al*., 2006; Ballard and Mallikarjunan, 2006) theorized that using an external head gas, such as nitrogen, might reduce fat uptake in breaded chicken products. While Innawong *et al*. (2006) found no significant difference in the oil uptake by chicken nuggets fried in a typical pressure fryer versus those fried with nitrogen, Ballard and Mallikarjunan (2006) found a significant increase in the oil content of chicken nuggets fried with nitrogen versus those fried in a traditional pressure fryer. Garayo and Moreira (2002), however, successfully reduced oil uptake in potato chips by frying under a vacuum. The fat content was reduced by more than 10% when fried at a vacuum pressure of 3.115 kPa instead of at atmospheric conditions. Lloyd *et al*. (2004) investigated the possibility of using controlled dynamic radiant heating as a finish heating method for par-fried French fries. It was found that radiant heating (13.0% oil by weight) gave a significantly lower fat content than immersion frying (19.2% oil by weight).

2.1.2.2 Coatings and Batters

Edible coatings may be a way to reduce the amount of oil absorbed during deep-fat frying without negatively affecting other quality attributes like taste, texture, and product color (Hansen, 1998). An edible film is a thin layer of edible material “formed on a food as a coating or placed (pre-formed) on or between food components” (Krochta and Mulder-Johnston, 1997). Besides reducing oil absorption, edible films and coatings have been shown to improve breading adhesion, increase moisture content, and enhance texture and appearance (Antonova *et al.*, 2002).

One of the most common uses of edible coatings on fried foods is for reduction of fat content, which has been correlated with an increase in moisture content. The edible films form a thermally induced protective layer on the surface of the samples (Antonova *et al.*, 2002). This protective layer acts as a selective barrier to inhibit the transfer of moisture and fat between the sample and the frying medium.

Collagen, caseins, and cellulose derivatives such as carboxy methylcellulose (CMC), methylcellulose (MC), and hydroxypropyl methylcellulose (HPMC) have all been used to significantly reduce oil absorption during frying (Debeaufort *et al.*, 1998). MC and HPMC have been used to reduce oil absorption during frying of extruded and frozen French fries and onion rings (Gold, 1969).

Hydrophilic biopolymers can be used as water binders in a coating to reduce water loss from the crust (Mellema, 2003). A reduction in water loss would also reduce oil uptake (Pinthus *et al.*, 1993). Most commercial biopolymer coatings used to reduce fat uptake are polysaccharide coatings. Corn zein (Herald *et al.*, 1996) and gellan gum (Williams and Mittal, 1999) coatings have been claimed to reduce fat diffusivity. Feeny *et* *al*. (1993) reported a 28% reduction in oil uptake when corn zein (CZ) was used as an edible coating in French fried potatoes. Fan and Arce (1986) reported the use of amylose as a surface coating to reduce fat uptake during frying. Olson and Zoss (1985) spray aqueous gelatin solutions on battered and breaded meats. Oil absorption was reduced during frying due to the grease resistance of the films. Feeney *et al*. (1993) applied zein coatings to potatoes prior to deep-fat frying that reduced the oil content by 20 to 40% compared to uncoated products. Polansky (1993) used collagen solution (1 to 2% w/w) to reduce the amount of absorbed oil in potato slices by more than 40% compared to uncoated slices. A mixture of soy protein isolate (10% w/w) and gellan gum (0.5% w/w) was recommended by Rayner *et al*. (2000) for coating foods to reduce oil uptake during deep-fat frying.

2.1.2.3 Modification of Frying Medium

According to current theory, frying oil with either a high viscosity or a viscosity that increases steeply upon cooling will decrease oil uptake, because the flow of oil is hindered, especially in smaller holes or pores (Mellema, 2003). However, high viscosity will also lead to less easy drainage of oil from the food (Moreira *et al*., 1999). No techniques are available currently that significantly affect total oil uptake (Mellema, 2003).

2.2 Frying Oil

2.2.1 Chemical Changes of Oil during Frying

Frying oil undergoes many changes during the frying process, mostly due to the high temperature and presence of water vapor. The presence of steam will lead to hydrolysis, the end products of which include free fatty acids and partial glycerides (deMan, 1999). Autoxidation occurs from contact with air. Oxidation products include oxidized monomeric, dimeric, and oligomeric triglycerides, and volatile compounds such as aldehydes, ketones, alcohols, hydrocarbons, and sterols. Thermal degradation from high oil temperatures causes accelerated deterioration of the oil and the formation of free fatty acids. Free fatty acids will lead to foaming and will alter the viscosity, flavor, and color of the oil (Fellows, 2000).

2.2.2 Effect of Oil Quality on Fried Foods

The quality of frying oil heavily influences the final quality of the products fried in it. It is commonly accepted that there are five stages that frying oil goes through during its lifetime (Blumenthal, 1991). The first stage is break-in oil when foods produced are raw and light in color, cooking odors are not present, product surfaces are not crispy and little oil is absorbed. The second stage is fresh oil when foods are partially cooked, there is slight browning at the edges of the product, product surfaces begin to crisp and there is slightly more oil absorption. The next stage is optimum oil when foods are golden brown-in color, products are fully cooked with crisp, rigid surfaces, pleasant cooking odors exist, and there is optimal oil absorption. The fourth stage is degrading oil when products have spotted surfaces and are becoming limp and there is excess oil absorption. The final stage is runaway oil when foods have dark, hard surfaces, the product is excessively oily and not fully cooked, and unpleasant odors and flavors are present.

2.3 Frying Methods

2.3.1 Pressure Frying

Frying in a closed pressurized system raises the boiling points of both frying oil and product moisture, increasing the rate of heat transfer to the food and shortening frying time. In addition, foods fried under pressure usually preserve more moisture and flavor (Shyu *et al*., 1998). Unfortunately, a large food load is required to create enough steam to allow for pressurization. Both Innawong *et al*. (2006) and Ballard and Mallikarjunan (2006) experimented with using nitrogen gas as the pressurizing medium for deep fat frying. The thought was that an external pressurizing medium, such as nitrogen gas, would create the same good fried food qualities as traditional pressure frying while allowing for smaller food loads and less waste. An additional bonus could be the preservation of frying oil quality, degraded more quickly by the presence of steam.

Innawong *et al*. (2006) compared chicken nuggets fried with nitrogen gas with chicken nuggets fried in a traditional pressure fryer, in terms of moisture retention and lipid uptake. For his research, the author modified a commercial pressure fryer by adding an exhaust tube and a T-shaped tube to allow for the flow of nitrogen into the vessel. Innawong *et al*. (2006) found that the time to reach the desired frying pressure was much shorter for nitrogen than for steam. In addition, products fried with nitrogen gas were juicier. No significant differences were found in terms of breading adhesion, crust fat content, or color. Nitrogen fried chicken nuggets had a softer crust, but were more tender than nuggets fried under atmospheric conditions. When comparing the oil quality, the nitrogen gas increased the life of the frying oil compared to traditional pressure frying, by slowing the degradation of the oil (Innawong, 2001).

Ballard and Mallikarjunan (2006) compared chicken nuggets coated with edible film coatings and fried with two pressure sources (nitrogen and steam). They concluded that nuggets fried under nitrogen gas had similar or better quality when compared to samples fried with steam, in terms of moisture and fat content, juiciness, and color. Ballard and Mallikarjunan (2006) also investigated the effect of edible film coatings and pressure source (nitrogen or steam) on crispness of chicken nuggets. They determined crispness using an ultrasonic non-destructive evaluation system developed by Antonova *et al*. (2002). Samples fried using nitrogen had a higher ultrasonic velocity than samples fried with steam and were therefore determined to be crispier. A sensory panel using forty untrained subjects suggested there were no differences in consumer acceptance of steam-fried chicken nuggets versus nitrogen-fried chicken nuggets, in terms of crispness, oiliness, juiciness, and flavor.

2.3.2 Vacuum Frying

During frying, the increased temperature causes boiling of the oil and product moisture. The water in the fried foods evaporates leaving voids behind. Some oil will enter the product to fill the voids; however, most oil is absorbed into the core of the product during cooling. Since the product's crust will have the highest temperature, it will lose the most moisture, leaving more voids for oil (Mellema, 2003). During cooling, this surface oil will enter the product core because of pressure differences between the core and its surroundings (Garayo and Moreira, 2002).

During vacuum frying, reduced pressure is applied, lowering the boiling points of both the frying oil and the moisture in food. This allows food to be fried at lower temperatures, preserving their natural colors and flavors (Shyu *et al.*, 1998). In addition, oil life and quality are increased because the low temperatures and pressures reduce deterioration and oxidation of the frying oil (Imai, 1989).

Shyu *et al*. (1998) compared the oxidative stability of palm oil, lard, and soybean oil during vacuum frying. They did not do a direct comparison to other frying processes, but they did determine that "vacuum frying imparted a lower oxidative degradation on the frying oil than the typical frying."

Shyu and Hwang (2001) vacuum fried apple chips at 3.115 kPa and 90, 100, and 110°C. They determined the optimum frying temperature and time to be 100-110°C and 20-25 min, respectively.

Garayo and Moreira (2002) produced vacuum-fried potato chips with decreased oil content (27% wet basis) compared to atmospheric-fried potato chips (40% wet basis). The vacuum-fried potato chips were fried at an oil temperature of 144°C and a vacuum pressure of 3.115 kPa. The atmospheric-fried potato chips were fried at 165°C and 101.35 kPa. They also found that vacuum-fried chips had higher volume shrinkage and were softer and lighter than atmosphere-fried chips. They theorize that a slower-forming crust under vacuum conditions causes the reduced oil content. This allows less oil to be held at the surface, leaving less oil to be absorbed into the core. Potato chips were also fried under vacuum at 16.661 and 9.888 kPa and 118 and 132°C.

In a patent for parfried potato strips, Minelli and Harney (2000) described the optimal parameters for vacuum frying. Temperatures below 290°F are preferred, because, above that level, vacuum-frying benefits, such as improved moisture removal efficiency and better flavor retention, are reduced and become comparable to atmospheric frying at the same temperature. Below 240°F, however, moisture removal becomes slow, increasing frying time and/or vacuum levels, which, in turn, increase processing costs. Pressures between 34 and 68 kPa are preferred. As pressures become lower, the boiling point of water decreases, decreasing the moisture removal rate. This increases the traditional frying behavior of vacuum frying. At higher pressures, the cost of creating and maintaining the vacuum becomes very great.

Though some work has also been done on carrot, apple, and potato chips, there has been no work on the vacuum frying of breaded foods.

2.4 Fried Product Analyses

2.4.1 Breading Adhesion

Maskat and Kerr (2004) shook fried chicken breasts on an orbital shaker (VMRbrand, VMR Scientific Products, West Chester, PA). Innawong (2001) measured breading adhesion using a method described by Suderman and Cunningham (1983), in which ten pieces of the fried product (in this case, chicken nuggets) are shaken in a standard wire sieve (No. 4 US Sieve) for 1 minute. Accumulated breadcrumbs were weighed and used to calculate percentage coating loss.

2.4.2 Color

Shyu *et al*. (2005) measured the surface color of vacuum-fried carrot chips with a colorimeter (Nippon Denshoku 90 color difference meter, Tokyo, Japan). They expressed color as Hunter L, a, and b values. Garayo and Moreira (2002) used a Hunter Lab Colorimeter Labscan XE (Hunter Associates Laboratory, Reston, VA) to measure color of vacuum-fried potato chips. Both Innawong *et al*. (2006) and Ballard and Mallikarjunan (2006) used a Minolta chromameter (Model CR-300, Minolta Camera, Ltd., Osaka, Japan) to measure the L*, a*, and b* values of chicken nugget crusts. Moyano *et al*. (2002) used this same instrument to determine French fry color, Baik and Mittal (2003) used it for fried tofu, and Ramirez and Cava (2005) used it for fried pork chop loins. Patterson *et al*.

(2004) used a Minolta chromameter Model CR-200 for akara (fried cowpea paste). Dogan *et al*. (2005) used a Minolta color reader (CR-10) on fried chicken nuggets. Hue angle was used to characterize color.

2.4.3 Juiciness

Innawong *et al*. (2006) measured juiciness of chicken nuggets using a press method described by Mallikarjunan and Mittal (1994), in which the core of the nugget was pressed with 20 kPa pressure for 1 minute between aluminum foil, pre-weighed filter paper, and Plexi-glass plates. The filter papers were re-weighed following the press and the weight increase was correlated to the product's expressed juice.

Since juiciness is more qualitative than quantitative, sensory panels, trained and untrained, are the most common way to determine juiciness acceptability of foods. Sensory panels can be influenced by personal biases, ambiguity of the survey, and individual variability (Ballard, 2003), but there is not a consensus on a better way to determine juiciness. Recently, sensory testing has been used to determine juiciness of tomatoes (Plaehn and Lundahl, 2006), apples (Peneau *et al*., 2006), chicken (Xiong *et al*., 2006), pork (Teye *et al*., 2006), ostrich meat (Hoffman *et al*., 2006), and buffalo meat (Thomas *et al*., 2006).

Xiong *et al*. (2006), for example, used a consumer panel, consisting of 74 people, to evaluate the acceptability of the juiciness of chicken breasts as well as overall texture and tenderness, appropriateness of tenderness, and intensity of tenderness. These results, along with those from a seven-member trained panel were correlated to instrumental measurements.

Hoffman *et al*. (2006) used an 8-member trained panel to evaluate ostrich meat in terms of initial juiciness, sustained juiciness, intensity of ostrich aroma, impression of tenderness, amount of residue, and overall ostrich flavor. The initial juiciness was described as “the amount of fluid exuded on the cut surface when pressed between the thumb and forefinger,” and was rated on a scale of 0 (extremely dry) to 100 (extremely juicy). The sustained juiciness was described as “the degree of juiciness perceived after the first two to three chews between the molar teeth,” and was also rated on a scale of 0 to 100.

2.4.4 Moisture Content

Ramirez and Cava (2005) determined the moisture content of fried pork loin chops by drying 5 g samples at 102°C until a constant weight was reached (AOAC, 2000). Maskat *et al*. (2005) determined the moisture content of surface layers of coated chicken breasts by oven drying at 105°C (AOAC, 2000). Dogan *et al*. (2005) dried fried chicken nuggets in a forced convection oven at 105°C until constant weight was reached (AOAC, 2000). Shyu *et al*. (2005) dried vacuum-fried carrot chips in a vacuum oven to a constant weight at 70°C to determine moisture content (MC). Maskat and Kerr (2004) measured the weight difference of fried chicken breasts before and after drying at 100°C in a vacuum oven for 24 hours (AOAC, 2000). Garayo and Moreira (2002) dried ground vacuum-fried potato chips in a forced air oven at 105°C for 24 hours (AACC, 1986) to determine MC. Moyano *et al*. (2002) dried French fries and Pedreschi and Moyano (2005) dried potato chips in a convection oven at 105°C until constant weight was reached. Holownia *et al*. (2000) determined the MC of fried marinated chicken strips using a Genesis SQ 25 Super ES freeze dryer (Virtis Co., Gardiner, NY). The pressure in the chamber was kept below

3.2 kPa and the temperature was 20^{o}C. Innawong *et al*. (2006) also used a freeze dryer to determine MC of chicken nuggets.

2.4.5 Oil Content

Kita and Lisinska (2005) used Soxhlet's method (AOAC, 2000) to determine fat content of French fries with a Buchi B-811 universal extraction system (Buchi Labortechnic AG, Flawil, Switzerland). Shyu *et al*. (2005) determined oil content (OC) of vacuum-fried carrot chips gravimetrically by Soxhlet extraction (AOAC, 2000). Dogan *et al*. (2005) used Soxhlet extraction with *n*-hexane for 6 hours on fried chicken nuggets (AOAC, 2000). Ballard and Mallikarjunan (2006) used method 991.36 (AOAC, 2000) with a Soxtec extraction unit to determine OC of chicken nuggets. Garayo and Moreira (2002) used the Soxtec System HT extraction unit (AACC, 1986) with petroleum ether to determine OC of vacuum-fried potato chips. Moyano *et al*. (2002) used a method by Bligh and Dyer (1959) to determine oil content of French fries. This method involves using a 1:2:0.8 (v/v/v) mixture of chloroform, methanol, and water. Pedreschi and Moyano (2005) also used this method on potato chips. Ramirez and Cava (2005) used the same method but with 1:2 chloroform/methanol mixture. Innawong *et al*. (2006) used method 960.39 (AOAC, 2000) to determine OC of freeze-dried chicken nuggets. Holownia *et al*. (2000) used a Labconco Goldfisch Fat and Oil Extractor (Labconco Corp., Kansas City, MO) with petroleum ether as the solvent to determine OC of freeze-dried edible film-coated chicken strips.

2.4.6 Texture

Dogan *et al*. (2005) determined texture of chicken nuggets in terms of fracturability or brittleness, which is defined as the force at the first significant break in the first positive bite area of the Texture Profile Analysis curve. A conical probe was attached to a texture analyzer (Lloyd Instruments, TA Plus, Hants, UK). Shyu *et al*. (2005) used a TA-XT2 texture analyzer (Stable Micro Systems Co. Ltd., Godalming, Surrey, UK) to determine the breaking force of vacuum-fried carrot chips. Pedreschi and Moyano (2005) did the same with potato chips. Kita and Lisinska (2005) determined texture of French fries using an Instron 5544 instrument with a rectangular attachment. The velocity of the head was 250 mm/min with a 100 kg load cell. Maximum shear force was determined. Patterson *et al*. (2004) used an Instron universal testing machine (model 1122, Instron Corp., Canton, MA) with a Kramer cell to characterize the texture of akara. They determined peak force required to cut through the akara ball using a 500 kg load cell with a crosshead speed of 50 mm/min. Garayo and Moreira (2002) also used a TA-XT2 Texture Analyzer for a rupture test on vacuum-fried potato chips. Innawong *et al*. (2006) used a Kramer shear unit with a Sintech/MTS universal testing machine (model 5G, MTS, NC) to characterize the texture of chicken nuggets. Peak load, total energy to peak load, and energy to failure point were calculated.

2.5 Health Issues

Coronary heart disease is the single leading cause of death in the United States. It caused 479, 305 deaths in 2003 alone. Cardiovascular disease was the cause of 37.3% of all deaths in the United States in 2003 (American Heart Association, 2006). The excessive consumption of fat, especially saturated fat, has been linked to the development of cardiovascular disease. Dietary trans-fatty acids enhance the risk of developing coronary heart disease (Ruiz-Roso and Varela, 2001). While deaths from cardiovascular disease and coronary heart diseases have been decreasing over the last several years, there is still much to be concerned about. Excess fat consumption from fried foods can be a key contributor to coronary heart disease (Browner *et al*., 1991), as they can contain 10-40% oil (deMan, 1999). Browner *et al*. (1991) estimated that if all Americans reduced consumption of saturated fat, the corresponding reductions in cholesterol levels could reduce deaths from coronary heart disease by 5-20%, depending on age.

There is also an association between dietary fat and obesity. The prevalence of overweight, obese, and morbidly obese Americans increased significantly from the time the Third National Health and Nutrition Examination Survey (NHANES III) was performed between 1988-1994 (Kuczmarski *et al*., 1994) until a survey (NHANES 1999-2000) was performed by Flegal *et al*. (2002) from 1999-2000. Obesity is considered a pandemic and is associated with cardiovascular disease, type 2 diabetes, hypertension, sleep apnea, and certain cancers (Poirier *et al*., 2006).

In 1997, Swedish researchers discovered that cooking food at high temperatures can lead to the formation of acrylamide, a known neurotoxin and potential carcinogen (Erickson, 2004). Rats fed fried feed had N-(2-carbamoylethyl)valine (CEV) adduct levels ten times higher in their hemoglobin than rats fed unfried feed. This adduct is formed when acrylamide reacts with globin. In an analysis of the feed, fried feed had approximately fifteen times more acrylamide present than unfried feed (Tareke *et al*., 2000). Granda and Moreira (2005) investigated the possibility of vacuum frying potato chips to reduce the formation of acrylamide. The acrylamide content of vacuum fried potato chips was 94% less than traditionally fried potato chips. The lower temperatures used in vacuum frying (118-140^{o}C) compared to those in traditional frying (150-180^{o}C) were cited as the cause of the reduced acrylamide content. The biggest concern for the presence of acrylamide is in starch-rich foods (i.e. potato chips, French fries); however, protein-rich foods, especially ones coated in batter and breading before being fried, still contain a not insignificant amount of acrylamide (Tareke *et al*., 2002).

Conclusions

Recently, the United States Food and Drug Administration (FDA) began requiring that the amount of *trans* fat in a product be added to its label, thus increasing the awareness of the fat content of the foods Americans eat. While there is concern about the healthiness of fried foods, their popularity is not waning. There is clearly still a need for more research into the development of ways to create healthier (i.e. low-fat) fried foods.

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CHAPTER 3

THE EFFECT OF EXTERNAL PRESSURIZING MEDIA ON QUALITY OF BREADED FRIED FOODS

ABSTRACT

Pressure frying is a popular way to create juicy and tender foods, but it is dependent upon large food loads to generate the pressure required inside the fryer. The use of nitrogen gas as an external pressurizing media has been explored in previous studies. This study evaluated the use of compressed air, much easier and less expensive to obtain than nitrogen gas, as a pressurizing media during deep-fat frying. Fish sticks were fried at two temperatures (175oC and 190oC) and two pressures (163 kPa and 184 kPa) by either traditional pressure frying or external pressurizing media (nitrogen gas or compressed air). The products were evaluated in terms of color, juiciness, moisture content, oil content, and texture. Overall, products fried using nitrogen gas and compressed air were not found to be significantly different ($p < 0.05$). In addition, these products had significantly lower ($p < 0.05$) crust oil contents and were more tender than steam-fried fish sticks. Frying with nitrogen or air reduced the oil uptake in the crust by 31.8% and 25.6%, respectively, compared to frying with steam.

Keywords: pressure frying, nitrogen gas, fish sticks, compressed air

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INTRODUCTION

Fried foods are popular around the world. One of the main reasons for this popularity is the “textural dichotomy of the food: dry and crispy crust, tender inside” (Mellema, 2003). Popular fried foods include fish sticks - 19.51 million pounds ($41.53 million value) were produced in 2001 in the U.S. alone (Gupta, 2004).

Food products fried via pressure frying are more juicy and tender than foods fried at atmospheric pressure (Mallikarjunan, Chinnan, and Balasubramaniam, 1995; Rao and Delaney 1995). Currently, pressure fryers depend on the steam released from large food loads to generate pressure inside the fryer (Innawong, Mallikarjunan, Marcy, and Cundiff, 2006), which can lead to wasted food products in commercial applications. Using nitrogen gas as the pressurizing medium during frying has been shown to give food products of equal or better quality than traditional pressure frying, while allowing for smaller fry loads (Innawong *et al.*, 2006).

During frying, oil quality is greatly reduced. The oil is hydrolyzed and oxidized, forming free fatty acids and polar compounds. Steam released by food products during pressure frying also greatly increases the degradation of the oil. As oil degrades, it negatively affects the quality of food being fried, in terms of color, texture, and flavor (Blumenthal, 1991). When nitrogen gas is used to generate the pressure for frying, oil life can be doubled (Innawong, 2001).

The objective of this study was to evaluate the use of compressed air, which is less expensive and easier to obtain than nitrogen gas, as a pressurizing medium during deep-fat frying of fish sticks. Experiments were conducted to compare the effects of compressed air, nitrogen gas, and traditional pressure frying on the quality attributes (crust color, juiciness, moisture content, oil content, and texture) of fried fish sticks.

MATERIALS AND METHODS

Sample Preparation

Par-fried frozen fish sticks were obtained from Icelandic USA, Inc. (Newport News, VA). The fish sticks consisted of 42% minced pollock and were par-fried in hydrogenated soybean oil. The breading consisted of enriched bleached wheat flour, enriched yellow corn flour, and cellulose gum. They were packaged in dry ice during shipping. Upon arrival, the fish sticks were placed in a freezer (-18°C), where they were stored prior to frying.

Frying Experiment

Fish sticks were fried in a modified pressure fryer (Model 500C, Henny Penny, Inc., Eaton, OH, Figure 3.1) using commercial soybean oil (Bakers & Chefs, North Arkansas Wholesale Company, Inc., Bentonville, AR). Samples were fried at one of two temperatures (175°C and 190°C) and one of two pressures (163 kPa and 184 kPa). These temperatures and pressures were chosen because data exists for other products fried at these settings (Innawong *et al.*, 2006). Three pressure sources, compressed air, nitrogen gas, and steam released from the food, were used to generate the required pressure in the fryer.

Using a system developed by Innawong (2001), a tee replaced the exhaust tube used to connect the operating valve to the fry pot. A universal connection was attached to the tee, allowing for links to either the nitrogen gas tank or the compressed air valve, as needed. The amount of pressure (163 kPa or 184 kPa) was set using weights in the operating valve.

Each treatment combination included 1200 g of product fried for a constant time of 240 s. This was enough time for the internal temperature of the fish sticks to reach 100°C, which was determined in a preliminary test. Figure 3.2 shows a typical internal temperature profile of fish sticks during frying in this research. Internal temperature was determined using thermocouples connected to a data logger (Model 21X, Campbell Scientific, Inc., Logan, UT). There was an average 30 s delay for closing and opening the fryer. There were three replications for each treatment (pressure, temperature, pressure source) combination.

Color Analysis

The color of the products was measured immediately after frying using a Minolta chromameter (Model CR-300, Minolta Camera, Ltd., Osaka, Japan, Figure 3.3) calibrated to a white plate. L*, a*, and b* values were used to characterize color of the fried fish stick crusts. The test was replicated three times using three different samples.

Texture Analysis

Texture of the products was analyzed using a universal testing machine (Model 5G, MTC, NC, Figure 3.4) with a Kramer shear unit (Figure 3.5) attached. This test simulates biting into the product. The load and crosshead speed were maintained at 5 kN and 100 mm/min, respectively. The peak load (N/kg), total energy to peak load (N-mm/kg), energy to failure point (N-mm/m^3) were determined and used to characterize the texture of the fried fish sticks.

Juiciness

The juiciness of the fried products was determined using a slight modification to the method developed by Mallikarjunan and Mittal (1994) method. In this study, a Carver press (Model C, Fred S. Carver, Inc., Menomonee Falls, WI, Figure 3.6) was used to apply pressure to the samples. One gram of core meat was placed between two sheets of aluminum foil, which were in turn placed between two pre-weighed filter papers (Whatman No. 5, 110 mm diameter). This sandwich was placed between two Plexi-glass plates (12.5 x 12.5 cm) and compressed with an applied load 3000 N for one minute. The amount of time and pressure was determined through a preliminary test. The weight increase of the filter papers was recorded as pressed juice. The test was replicated three times using three different samples.

Moisture and Fat Content

Moisture and fat contents were determined for both the core and the crust of the fried products. After separation, the mass of the crust and core of each component were measured, wrapped in a pre-weighed filter paper and placed inside a pre-weighed cellulose extraction thimble. Samples were frozen overnight then freeze-dried (The Virtis Company, Inc., Gardiner, NY, Figure 3.7) for three days. The thimbles containing the samples and filter paper were weighed again to determine the moisture content. Freeze drying allows the removal of moisture from the product without the destruction of its porous structure (Ateba and Mittal, 1994). The test was replicated three times.

A subsequent fat analysis was conducted on the samples. The fat content was determined using a Soxtec extraction unit (Figure 3.8) and AOAC method 991.36 (AOAC, 2000) with petroleum ether as the solvent. The test was replicated three times.

Statistical Analysis

The effect of pressure source, pressure, and temperature on color, juiciness, moisture content, oil content and texture of fried fish sticks was evaluated using a three-way factorial design with three levels of pressure source and two levels each of pressure and temperature. The SAS statistical software package (version 9.0, 2004) was used to conduct an analysis of variance (ANOVA) and Fisher's least significant difference (LSD) test, which was used to determine significant differences between treatments means. Alpha (α) was set at 0.05 for all analyses.

RESULTS AND DISCUSSION

Effect of Pressure

Pressure as a main effect did not significantly influence ($p > 0.05$) any quality measures of the fried fish sticks (Table 3.1 – Table 3.3). These results are contradictory to those of Innawong *et al.* (2006), who found that pressure significantly affected ($p < 0.05$) moisture content, oil content, and texture of fried chicken fillets. In the case of this research, the insignificance of pressure may be due to differences in pressurizing media, in terms of the length of time each took to reach the specified frying pressure. It took longer for the specified pressure to be reached during traditional pressure frying because the products' internal moisture had to be heated, evaporated, and then released from the product, before it was able to build up inside the fryer. The reduced time at the specified pressure might have reduced the effect that pressure would have on the products being fried.

The interaction of pressure and pressure source did significantly influence ($p < 0.05$) core oil content. The interaction of temperature and pressure significantly affected ($p < 0.05$) peak load.

Juiciness

Juiciness was not significantly affected ($p > 0.05$) by temperature, pressure, source of pressure, or any combination thereof (Table 3.4 – Table 3.6). Ballard and Mallikarjunan (2006) also found that pressure source had no significant effect on juiciness. Innawong *et al*. (2006), on the other hand, found that frying with nitrogen gas increased juiciness of fried chicken fillets compared to traditional pressure frying. In addition, Innawong *et al*. (2006) found that an increase in oil temperature decreased juiciness of chicken fillets. The disparity between the results from this study and those conducted by Ballard and Mallikarjunan (2006) and Innawong *et al*. (2006) suggests that the method used to measure juiciness in this research might need to be re-evaluated. On the other hand, the differences could be due to different product and batter formulations. The other researchers both fried chicken products, while fish was used in this research. The natural juices and oils in fish differ from those of chicken and might be affected differently by the frying process or the techniques used for measurement. The meat of the products also differed in structure. The structure determines the ease with which moisture migrates from the interior to the exterior of foods during frying (Ateba and Mittal, 1994). Moisture migration would affect juiciness, as moisture is one of the components of the juiciness of a food product. In addition, the breadings used in this research contained cellulose gum and that of Ballard and

Mallikarjunan (2006) contained whey protein isolate or methylcellulose, while the breading in the study by Innawong *et al*. (2006) did not. Edible coatings, such as cellulose gums, inhibit moisture migration during frying (Antonova, Mallikarjunan, and Chinnan, 2002), which could explain the differences in juiciness.

Effect of Temperature on Color

While neither pressure nor pressure source had a significant effect on color, temperature significantly affected ($p < 0.05$) both L* (lightness) and a* (green-red chromaticity) (Table 3.7). A higher L* value means that the fish sticks were lighter in color, while higher a* values indicate that more Maillard reactions are occurring (Garayo and Moreira, 2002). Maillard reactions are a form of non-oxidative browning (i.e. the increase in the red color of the fish sticks with temperature). Visually, fish sticks fried at 190^{o}C were dark brown in color (L* = 77.85, a* = 2.57), while those fried at 175^{o}C were more golden brown (L* = 77.85, a* = 9.67). This relationship between temperature and color is intuitive, because the velocity of Maillard reactions is affected by temperature. Ballard and Mallikarjunan (2006) found that chicken nuggets fried with nitrogen were significantly lighter in color than traditionally-fried chicken nuggets, while Innawong *et al*. (2006) found no significant difference between the color of nitrogen-fried chicken fillets and the color of traditionally-fried chicken fillets. Temperature and time of frying are the most important factors affecting product color, thus it is not surprising that the source of pressure had no effect on color.

Effect of Source of Pressure on Moisture Content

While pressure source had no significant effect ($p < 0.05$) on core moisture content, there were significant differences between treatment means (Table 3.8). Fish sticks fried with air as the pressurizing medium had significantly higher moisture contents (70.47%) in the core of the product than fish sticks fried with nitrogen (67.86%), while the core moisture content of nitrogen-fried fish sticks was also less than traditionally-fried fish sticks (68.69%), though not significantly so. These results are similar to those of Ballard and Mallikarjunan (2006) who found that nitrogen-fried chicken nuggets had statistically lower core moisture contents than steam-fried nuggets. Innawong *et al*. (2006), however, found that chicken fillets fried with nitrogen were shown to have significantly higher core moisture contents than those fried with steam.

According to Ballard and Mallikarjunan (2006), the larger fry load used by Innawong *et al*. (2006) resulted in a temperature drop that reduced the amount of moisture loss from the product. The fry load in this research was equivalent to that used by Innawong *et al*. (2006) and therefore, prevents the same line of reasoning in this situation. The products used in the research by Innawong *et al*. (2006) did not contain edible coatings, while both this research and the research done by Ballard and Mallikarjunan (2006) involved products that did contain them. Edible coatings, such as cellulose gums and whey protein isolate, inhibit moisture migration during frying (Antonova, Mallikarjunan, and Chinnan, 2002), which could explain the differences in moisture content effects.

Source of pressure also significantly affected ($p < 0.05$) the crust moisture content (Table 3.8). Traditional pressure frying, where steam generated from the frying products is the pressure source, gave significantly lower crust moisture contents (33.46%) than either frying with compressed nitrogen (36.85%) or air (36.27%). The difference between crust moisture content for air and nitrogen was not significant. Innawong *et al*. (2006) also found that steam gave lower crust moisture contents than nitrogen, though the differences were not significant. During pressure frying, the internal moisture of the food products is heated, evaporated, and then released into the fryer through pores in the food. This release of steam allows for the slow build up of pressure within the fryer. For pressure to build up in the fryer, moisture must first be removed from the crust. With the use of external pressurizing media, the specified pressure is reached shortly after the fryer lid is closed. The external pressure is most likely greater than the pressure created by the steam attempting to escape, thus inhibiting the escape of moisture from products being fried with nitrogen or compressed air. This accounts for the lower crust moisture contents found in traditionally pressure-fried fish sticks.

Effect of Temperature on Crust Moisture Content

Temperature also significantly affected ($p < 0.05$) the crust moisture content (Table 3.9). Products fried at 190°C had lower moisture contents in the crust of the products (33.50%) than those fried at 175°C (37.56%). Others have found similar results: Innawong *et al*. (2006) with chicken fillets, Shyu and Hwang (2001) with apple chips, and Shyu, Hau, and Hwang (2005) with carrot chips. During frying, the moisture in a product will vaporize when the local temperature is greater than the saturation temperature at the pressure of the fryer. Since the crust is in direct contact with the frying oil, it is at a much higher temperature than the saturation temperature and will, therefore, release moisture more rapidly than the core of the food. Since the temperature of liquid water cannot be greater than the saturation temperature, any further heat supplied to the water will result in increased evaporation of the remaining moisture (Rao and Delaney, 1995).

Effect of Source of Pressure on Oil Content

Source of pressure significantly affected ($p < 0.05$) both the crust and core oil contents of the fish sticks. No differences were found between the oil contents of fish sticks fried with nitrogen and fish sticks fried with air; however, traditional pressure frying had a significant effect on both crust and core oil contents (Table 3.10). Traditionally pressure-fried fish sticks had decreased oil content in the sample cores and increased oil content in the crusts of the products, when compared with fish sticks fried using external pressurizing media. Frying with external pressurizing media decreased the overall oil content, when compared to traditional pressure frying. Frying with nitrogen, for example, led to an 18% reduction in overall oil content vs. steam, while frying with air led to an 8% reduction.

When external pressurizing media was used, the full pressure was reached shortly after the lid of the fryer was closed. For traditional pressure frying, on the other hand, much more time was required for enough steam to be released from the products to produce the specified pressure. Since the external pressurizing media allowed the fish sticks to be fried for an overall longer period of time at the target pressure, there was more time for oil to be forced past the crust and into the core of the product, whereas the oil in the steam-fried fish sticks seems to have been restricted to the crust. This is also mostly likely the reason for the significance of the pressure/source of pressure interaction upon core oil content.

Another possibility behind the decreased oil contents in the crust of fish sticks fried with external pressurizing media is that the gas entering the fryer created bubbles, changing the turbulence of the oil, thus, changing the heat and mass transfer properties between the oil and the fish sticks. The presence of bubbles may also have inhibited the transfer of water vapor out of the fish sticks and migration of oil into the fish sticks by affecting the interfacial tension between the water vapor in the pores of the product and the oil surrounding it. Surface tension between the two is a key part of the condensation mechanism, the currently accepted mechanism for oil uptake (Saguy and Pinthus, 1995).

Innawong *et al*. (2006) did not find that source of pressure had a significant effect on crust oil content, while Ballard and Mallikarjunan (2006) found that frying with nitrogen increased crust and core oil content versus traditional pressure frying. The difference could be due to the different products being fried – fish instead of chicken – or possibly due to different batter formulations. Another product-specific possibility is the surface area of the foods being fried. Greater surface area results in increased oil uptake (Saguy and Pinthus, 1995). The products fried in the previous studies might have been larger, thus allowing for more contact between the product and the oil, or they might have greater surface roughness, which increases the overall surface area of the product.

Effect of Temperature on Core Oil Content

An increase in temperature led to a significant decrease ($p < 0.05$) in core oil content (Table 3.11). The core oil contents of fish sticks fried at 175°C and 190°C were 4.63% and 3.50%, respectively. Although not significant, the crust oil content was also less for higher temperatures than for lower temperatures. These results were somewhat surprising, given that in general, within a certain temperature range, increasing the frying temperature decreases the oil absorption (Fan and Arce, 1986), but overall, the amount of oil uptake is independent of temperature (Gamble, Rice, and Selman, 1987). The results, at least as far as the core oil content is concerned, are correlated to the moisture loss. In the core after frying at 175°C, the moisture content was lower and the oil content higher than after frying at 190°C. One possibility for the reduced core oil content at higher temperatures could be that some natural oils in the fish products were removed along with the rapidly evaporating moisture at the higher temperature, but not at the lower temperatures.

Effect of Source of Pressure on Texture

The source of pressure significantly affected ($p < 0.05$) the peak load, energy to peak load, and energy to failure point (Table 3.12). In all three cases, fish sticks fried with steam gave significantly higher values than fish sticks fried with air. Fish sticks fried with steam also had a significantly higher energy to peak load (158.97 J/kg) than those fried with nitrogen (134.64 J/kg). Higher values of peak load, energy to peak load, and energy to failure point correlate to harder, tougher fish sticks. In general, the results of Innawong *et al*. (2006) agree that nitrogen-fried foods have softer crusts and are more tender than steam-fried foods.

Rao and Delaney (1995) found that increased pressures during frying decrease the continuity of the breading starch network, resulting in softer textures. In contrast, frying with lower pressures created breading with open networks of starch and protein. The voids in this breading mostly contain air and oil, but little moisture, thus they are crisp. When external pressurizing media was used, fish sticks were fried at the specified pressure for a longer period of time than steam-fried fish sticks, where the pressure built slowly during the process, thus the continuity of the starch network in the crust was reduced in fish sticks fried with either nitrogen gas or compressed air. This resulted in softer textures.

Effect of Temperature on Texture

Temperature significantly affected ($p < 0.05$) both the peak load and energy to peak load, but not the energy to failure point (Table 3.13). An increase in temperature led to an increase in peak load, energy to peak load, and energy to failure point, meaning that higher temperatures lead to tougher, harder fish sticks. Innawong *et al*. (2006) also found that increasing temperature increased toughness of chicken nuggets. An increase in temperature results in further moisture loss from the crust of the product, creating a drier, crispier texture.

Although pressure was not found to significantly affect any texture measurement in this study, the pressure-temperature interaction did affect ($p < 0.05$) peak load. Texture is dependent upon both temperature and pressure and is related to the moisture loss in the crust of the product (Rao and Delaney, 1995). The internal moisture of the product being fried will evaporate when the local temperature is greater than the saturation temperature at the pressure of the fryer (Rao and Delaney, 1995). Each temperature-pressure combination will have a unique saturation temperature inside the fryer, thus each combination will have a unique effect on moisture loss and, thus, the texture of the crust.

CONCLUSIONS

With the exception of core moisture content, where frying with compressed air gave significantly higher values than nitrogen, no differences were found between products fried using nitrogen and those fried using compressed air. The use of both air and nitrogen as external pressurizing media created fish sticks that were more tender and lower in oil content than those created via traditional pressure frying. This suggests that the use of external pressurizing media during pressure frying can create healthier fish sticks, while reducing fry loads and increasing frying oil life. Further studies that explore the effect of compressed air (composed of 21% oxygen) as a pressurizing medium on the life of frying oil are suggested. In addition, consumer acceptance of products fried using external pressurizing media should be evaluated.

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Table 3.1 Effect of Pressure on Crust Color of Breaded Fried Fish Sticks

	Treatment Means		
Pressure (kPa)	L* – Lightness	a* - Red-green chromaticity	b* - Blue-yellow chromaticity
163	84.28^a	5.30^a	12.21^a
184	84.16^a	6.94^a	7.51^a

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.2 Effect of Pressure on Moisture and Oil Contents of Breaded Fried Fish Sticks

	Treatment Means			
	Moisture Content (%)		Oil Content (%)	
Pressure (kPa)	Core	Crust	Core	Crust
163	68.84^a	35.87^a	4.16^a	18.24^a
184	69.17^a	35.19^a	3.96^a	19.45^a

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.3 Effect of Pressure on Texture of Breaded Fried Fish Sticks

	Treatment Means		
Pressure (kPa)	Peak Load (kN/kg)	Energy to Peak Load (J/kg)	Energy to Failure Point (J/m^3)
163	32.14^a	139.71^a	1659.4^a
184	31.86^a	138.10^a	1707.3^a

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.4 Effect of Temperature on Juiciness of Breaded Fried Fish Sticks

	Treatment Means
Pressure (kPa)	Juiciness (%)
163	31.97[a]
184	30.96[a]

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.5 Effect of Pressure on Juiciness of Breaded Fried Fish Sticks

	Treatment Means
Temperature (^{o}C)	Juiciness (%)
175	32.07[a]
190	30.87[a]

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.6 Effect of Source of Pressure on Juiciness of Breaded Fried Fish Sticks

	Treatment Means
Source of Pressure	Juiciness (%)
Air	32.06[a]
Nitrogen	30.78[a]
Steam	31.58[a]

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.7 Effect of Temperature on Crust Color of Breaded Fried Fish Sticks

	Treatment Means		
Temperature (^oC)	L* – Lightness	a* - Red-green chromaticity	b* - Blue-yellow chromaticity
175	90.59^a	2.57^b	12.11^a
190	77.85^b	9.67^a	7.60^a

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.8 Effect of Source of Pressure on Moisture Content of Breaded Fried Fish Sticks

	Treatment Means	
Source of Pressure	Core (%)	Crust (%)
Air	70.47^a	36.85^a
Nitrogen	67.86^b	36.27^a
Steam	$68.69^{a,b}$	33.46^b

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.9 Effect of Temperature on Moisture Content of Breaded Fried Fish Sticks

	Treatment Means	
Temperature (^oC)	Core (%)	Crust (%)
175	68.75^a	37.56^a
190	69.27^a	33.50^b

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.10 Effect of Source of Pressure on Oil Content of Breaded Fried Fish Sticks

	Treatment Means	
Source of Pressure	Core (%)	Crust (%)
Air	4.07^{a}	17.35^{b}
Nitrogen	5.38^{a}	15.88^{b}
Steam	2.74^{b}	23.31^{a}

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.11 Effect of Temperature on Oil Content of Breaded Fried Fish Sticks

	Treatment Means	
Temperature (^{o}C)	Core (%)	Crust (%)
175	4.63^{a}	19.02^{a}
190	3.50^{b}	18.67^{a}

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.12 Effect of Source of Pressure on Texture of Breaded Fried Fish Sticks

	Treatment Means		
Source of Pressure	Peak Load (kN/kg)	Energy to Peak Load (J/kg)	Energy to Failure Point (J/m^{3})
Air	29.12^{b}	123.10^{b}	1377.1^{b}
Nitrogen	31.03^{a,b}	134.64^{b}	1671.0^{a,b}
Steam	35.84^{a}	158.97^{a}	2001.9^{a}

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Table 3.13 Effect of Temperature on Texture of Breaded Fried Fish Sticks

	Treatment Means		
Temperature (^oC)	Peak Load (kN/kg)	Energy to Peak Load (J/kg)	Energy to Failure Point (J/m^3)
175	27.48^b	122.96^b	1600.9^a
190	36.51^a	154.85^a	1765.8^a

Treatment means that are not significantly different ($p > 0.05$) within columns have the same exponent.

Figure 3.1 Modified Henny Penny Pressure Fryer used in this research

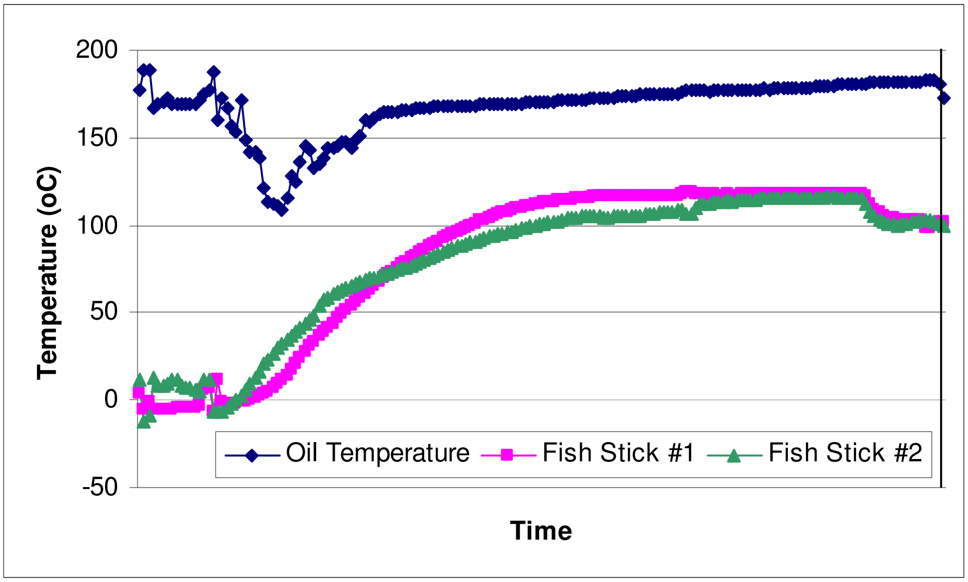

Figure 3.2 Typical internal temperature profile of fish sticks during frying in this research

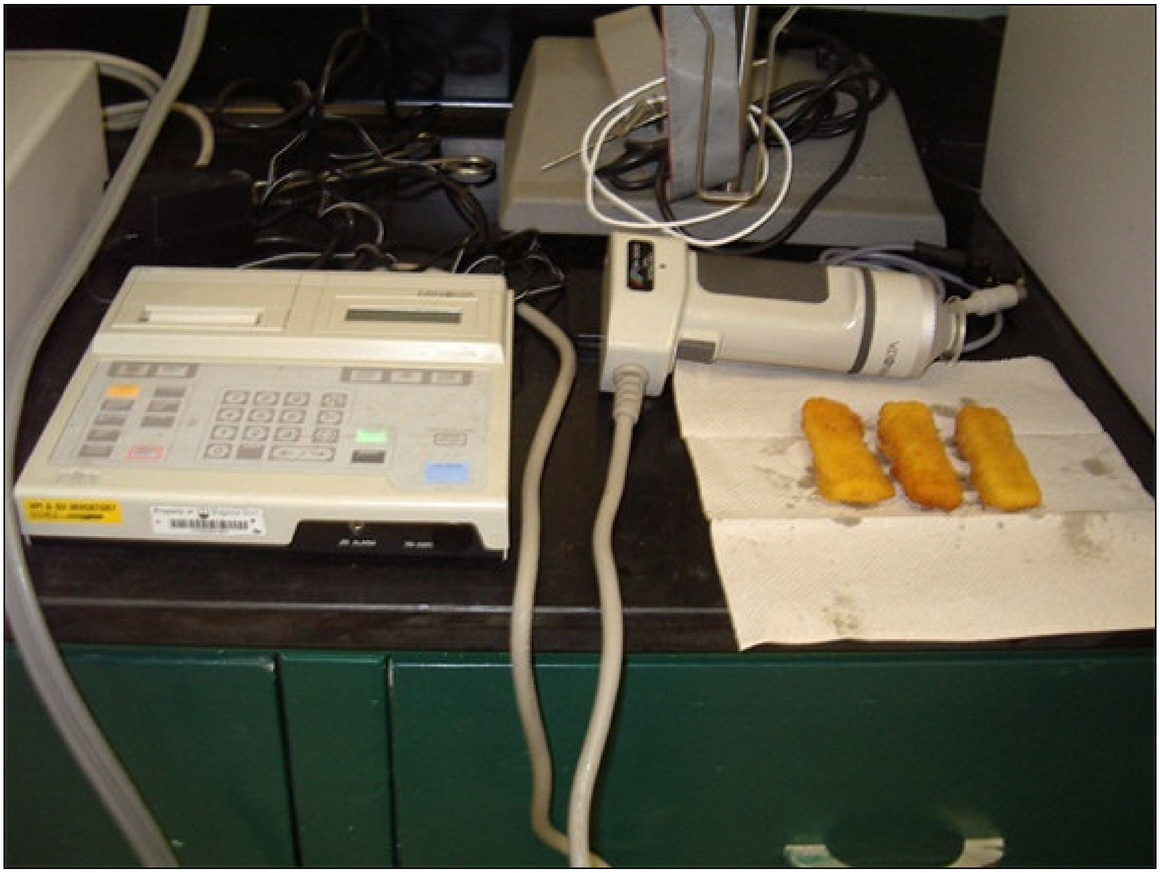

Figure 3.3 Minolta Chromameter used in this research

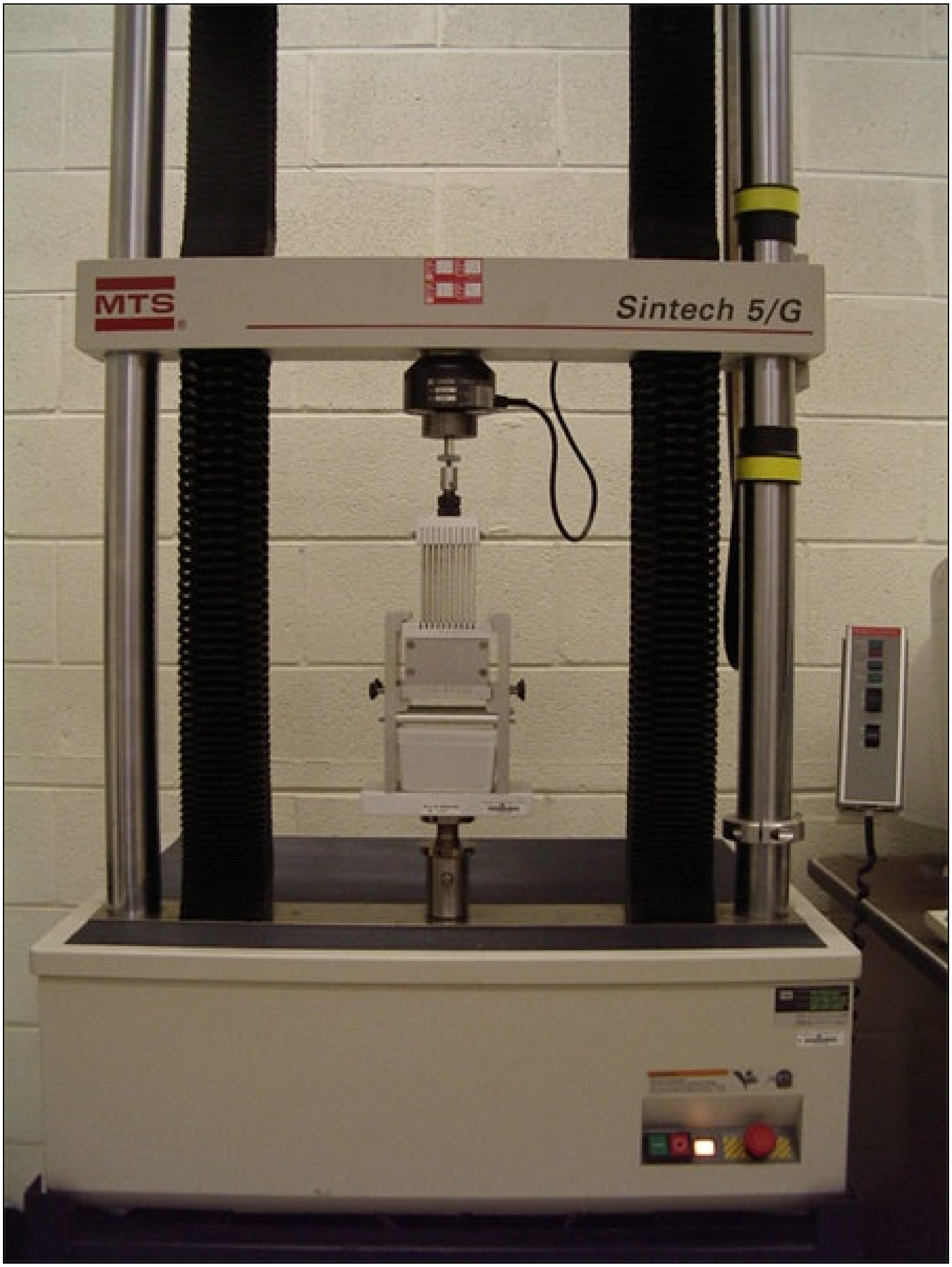

Figure 3.4 Universal Testing Machine, with Kramer Shear Unit attached, used in this research

Figure 3.5 Kramer Shear Unit attached to universal testing machine in this research

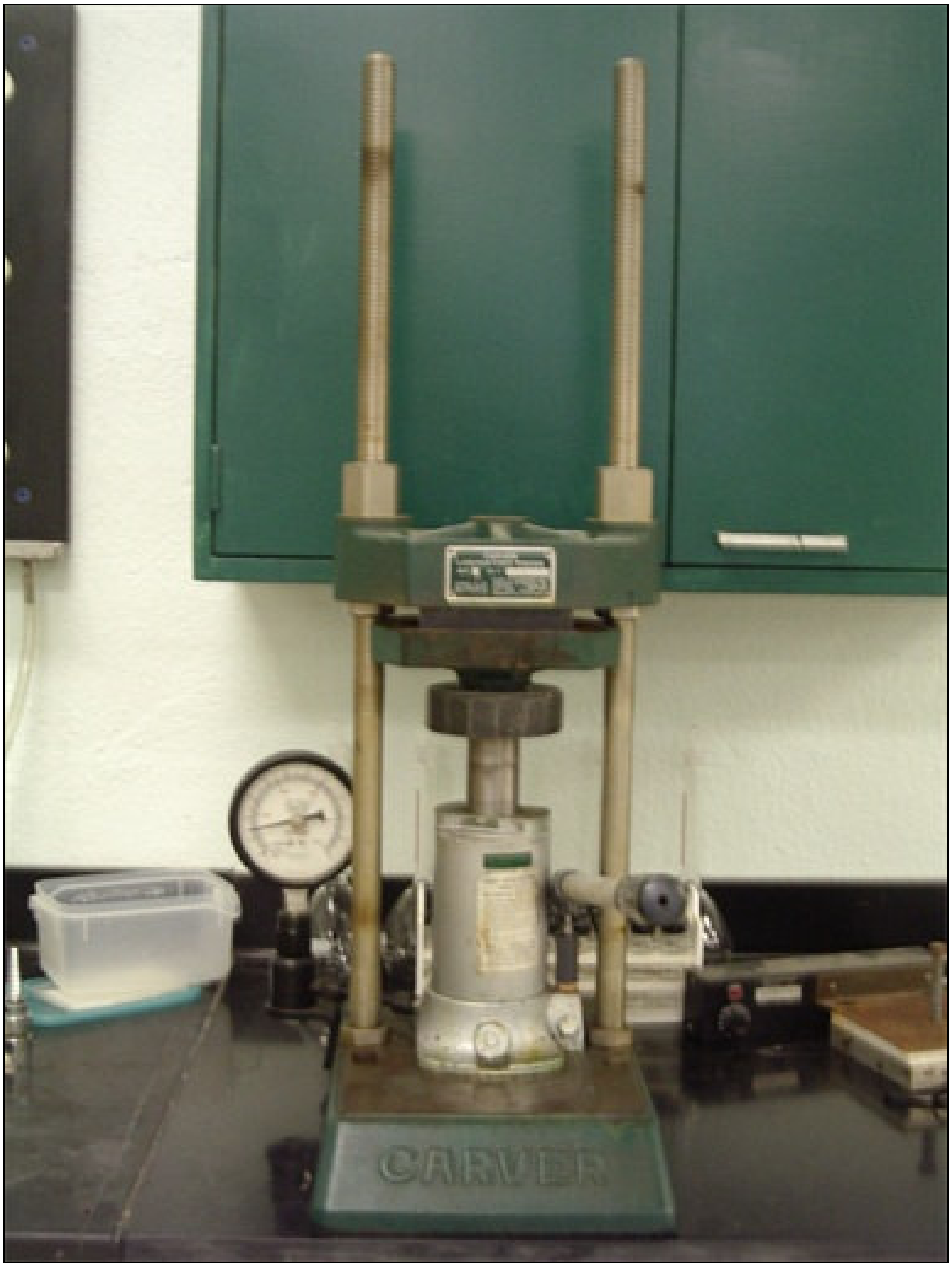

Figure 3.6 Carver Press used to determine juiciness in this research

Figure 3.7 Freezemobile Freeze Dryer used in this research

Figure 3.8 Soxtec Extraction Unit used to determine fat content in this research

CHAPTER 4

THE EFFECT OF VACUUM FRYING ON QUALITY OF BREADED FRIED FOODS

ABSTRACT

Vacuum frying, which occurs at pressures well below atmospheric levels, has recently been demonstrated to reduce fat content of various fried food products when compared to more conventional methods using steam for frying. This study evaluated the applicability of vacuum frying for breaded fried foods. Fish sticks were either pressure-fried at 163 kPa, atmospherically-fried at 101 kPa, or vacuum-fried at 41 kPa. Two temperatures were used for each pressure - 175^{o}C and 190^{o}C for the first two, 120^{o}C and 150^{o}C for the last. The products were evaluated in terms of color, juiciness, moisture content, oil content, and texture. The fish sticks vacuum-fried at 120^{o}C reached a maximum internal temperature of 40^{o}C and thus, were not fully cooked. Excluding this treatment, vacuum-frying did not have an effect on any quality attributes except juiciness. Overall, vacuum-fried fish sticks were comparable to pressure-fried fish sticks, except that the vacuum-fried fish sticks were significantly ($p < 0.05$) juicier.

Keywords: vacuum-frying, pressure frying, fish sticks

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INTRODUCTION

Deep-fat frying of foods has increased in both the United States and Europe over the past 40 years (Granda, Moreira and Tichy, 2004). These products are popular because they have a unique texture-flavor combination (Rao and Delaney, 1995). Breaded fried seafood products, in particular, are especially popular in the southern United States. In 2001 alone, the U.S. produced 19.51 million pounds ($41.53 million value) of fish sticks (Gupta, 2004). Despite their popularity, fried foods are considered by many to be unhealthy, because they contain a significant amount of fat, up of 1/3 of the product's weight (Mellema, 2003).

Food products fried via pressure frying are more juicy and tender than foods fried at atmospheric pressure (Innawong, Mallikarjunan, Marcy, and Cundiff, 2006). Currently, pressure fryers depend on the steam released from large food loads to generate pressure inside the fryer (Innawong *et al.*, 2006), which can lead to wasted food products in commercial applications. Much of the current research is focused on finding alternative frying methods, such as vacuum frying.

Vacuum frying occurs at pressures well below atmospheric levels. It has been used for some time in the frying of fruit chips (Minelli and Harney, 2000). Recently, Garayo and Moreira (2002) demonstrated the reduction of fat in potato chips caused by frying under vacuum conditions as opposed to atmospheric conditions. During frying, oil quality is greatly reduced. The oil is hydrolyzed and oxidized, forming free fatty acids and polar compounds. Steam released by food products during pressure frying also greatly increases the degradation. During vacuum frying, oil life and quality are increased because the low temperatures and pressures reduce deterioration and oxidation of the frying oil (Imai, 1989). No work has been done accessing the applicability of vacuum-frying for cooking breaded fried foods.

The objective of this study was to develop a vacuum fryer for use on breaded fried foods and to determine the effect of vacuum frying on the quality of fried fish sticks. Experiments were conducted to compare vacuum frying to traditional pressure-frying and atmospheric-frying.

MATERIALS AND METHODS

Sample Preparation

Par-fried frozen fish sticks consisting of 42% minced pollock meat were obtained from Icelandic USA, Inc. (Newport News, VA). The fish sticks were par-fried in hydrogenated soybean oil and their breading contained enriched bleached wheat flour, enriched yellow corn flour, and cellulose gum. They were packaged in dry ice during shipping, and, upon arrival, immediately placed in a freezer (-18^{o}C) for storage until frying.

Frying Experiment

Fish sticks were fried in a modified pressure fryer (Model 500C, Henney Penney, Inc., Eaton, OH) using commercial soybean oil (Bakers & Chefs, North Arkansas Wholesale Co., Inc., Bentonville, AR). Approximately 24 L of frying oil were used in a frying vat with dimensions of 36.2 x 42.5 x 31.7 cm. The fryer's exhaust tube that connected the operating valve to the fryer was replaced by a tee. A diaphragm vacuum pump (Model ME 8SI, Vacuubrand, Germany Figure 4.1) was attached to the tee using a universal connection.

Products were fried at a vacuum pressure of 41 kPa and two temperatures (120°C and 150°C). For comparison, samples were fried using steam generated from the product with 163 kPa of pressure at two temperatures (175°C and 190°C). Samples were also fried at two temperatures (175°C and 190°C) under atmospheric pressure conditions (101 kPa). When internal steam was used, the amount of pressure (163 kPa) was set using weights in the operating valve.

Each fry load consisted of 1200 g of product fried for a constant time of 240 s. In general, this was enough time for the internal temperature of the fish sticks to reach approximately 100°C. This was determined in a preliminary test using thermocouples connected to a data logger (Model 21X, Campbell Scientific, Inc., Logan, UT). There was an average 30 s delay for closing and opening the fryer. Three replications were performed for each treatment (pressure, temperature, pressure source) combination.

Color Analysis

A Minolta chromameter (Model CR-300, Minolta Camera, Ltd., Osaka, Japan) was used to determine the color of the product crust immediately following frying. The meter was calibrated to a white plate prior to use. Color was evaluated using L*, a*, and b* values. The test was replicated three times using three different samples.

Texture Analysis

A universal testing machine (Model 5G, MTC, NC), with a Kramer shear unit attached, was used to evaluate the texture of the fried products. A 5 kN load and 100 mm/min crosshead speed were the test settings. The peak load (N/kg), total energy to peak load (N-mm/kg), and energy to failure point (N-mm/m^3) were determined and used to characterize the texture.

Juiciness

A modified version of a press method developed by Mallikarjunan and Mittal (1994) was used to measure juiciness of the product cores. A sandwich consisting of one gram of core meat, surrounded by two sheets of aluminum foil, two pre-weighed filter papers (Whatman No. 5, 110 mm diameter), and two Plexi-glass plates (12.5 x 12.5 cm) was placed on a press (Model C, Fred S. Carver, Inc., Menomonee Falls, WI) and compressed with a 3000 N load for one minute. The amount of time and pressure was determined through a preliminary test. The increase in weight of the filter papers was recorded as pressed juice. The test was replicated three times using three different samples.

Moisture and Fat Content

Moisture and fat contents were determined for both the core and the crust of the fried products. The crust and core were separated, weighed, wrapped in a pre-weighed sheet of filter paper, and placed inside a pre-weighed cellulose extraction thimble. Samples were stored in a freezer (-16^{o}C) overnight then freeze-dried (The Virtis Company, Inc., Gardiner, NY) for three days. Freeze drying avoids destruction of a product's porous structure, while still allowing the removal of its moisture (Innawong *et al*., 2006). The moisture content was determined by re-weighing the thimbles containing the samples and filter paper after removal from the freeze dryer. The test was replicated three times. The dried thimbles were placed in a Soxtec extraction unit for determination of fat content, which was evaluated using AOAC method 991.36 (AOAC, 2000) with petroleum ether as the solvent. The test was replicated three times.

Statistical Analysis

The effect of treatments on product quality attributes was evaluated using a completely randomized design. Analysis of Variance (ANOVA) and Fisher's Least Significant Difference (LSD) test were performed using Statistical Analysis Software (version 9.0, 2004). SAS was also used to create box plots. Alpha (α) was set at 0.05 for all analyses.

RESULTS AND DISCUSSION

Effect of Temperature on Color

Both L* (lightness) and a* (red-green chromacity) were significantly affected ($p < 0.05$) by temperature (Table 4.1). The highest temperatures for each pressure (190^{o}C for pressure- and atmospheric-frying, 150^{o}C for vacuum-frying) had the lowest L* values, which translates into darker crust colors. These treatments are represented as treatments 2, 3, and 5, respectively, in Figure 4.2. As seen in Figure 4.2, frying at 190^{o}C, especially, made a distinct difference in L* value. These two treatments gave fish sticks with the darkest crust colors. The two treatments that took place at 190^{o}C had significantly higher ($p < 0.05$) a* values, indicating that more Maillard reactions occurred at the higher temperatures (Garayo and Moreira, 2002). Temperature affects the velocity and subsequent pathways of Maillard reactions, a form of non-oxidative browning. The reaction rate can increase 2-3 times for each 10^{o}C rise in temperature (Scandrett, 1997). In Figure 4.3, where treatments 2 and 3 took place at 190^{o}C, the distinct difference between these two treatments and the other four, occurring at lower temperatures, can be seen. The treatments did not significantly affect ($p > 0.05$) the b* value. This could be due to high variance in the data, as can be seen in Figure 4.4. Pressure did not statistically affect any color measurement. Garayo and Moreira (2002) found similar results with vacuum-fried potato chips.

Effect of Pressure on Juiciness

The fish sticks fried under vacuum (41 kPa) were significantly juicier ($p < 0.05$) than the fish sticks fried under traditional and atmospheric pressure conditions (Table 4.2). Upon visual inspection, however, it was clear that the fish sticks fried under vacuum (41 kPa) at 120°C were not fully cooked. The internal temperature of these fish sticks reached a maximum of 40°C. Because they weren’t fully heated, the moisture migration out of the core of the fish sticks was reduced, thus increasing the juiciness of the samples. Still, the fully-cooked fish sticks vacuum-fried at 150°C were juicier than fish stick fried under the other four treatment conditions. Others have found that an increase in pressure increases juiciness (Innawong *et al*., 2006; Moreira, Castell-Perez, and Barrufet, 1999; Mallikarjunan, Chinnan, and Balasubramaniam, 1995); however, potato chips fried under vacuum had higher moisture contents than atmospherically fried chips (Garayo and Moreira, 2002). This retention of moisture would affect the juiciness of the fried products. The atmospherically- and pressure-fried fish sticks had similar juiciness distributions, as can be seen in Figure 4.5, whereas the vacuum-fried fish sticks, despite the undercooked nature of treatment 6, had similar distributions to each other.

Effect of Pressure on Moisture Content

The fish sticks that were vacuum-fried at 120°C had significantly higher ($p < 0.05$) core and crust moisture contents than the other treatments (Table 4.3). This is probably due to the fact that the fish sticks fried with this treatment were not fully cooked, so their internal moisture did not escape. The fish sticks that were fried at atmospheric pressure (both temperatures) had the lowest core and crust moisture contents. Garayo and Moreira (2002) found that atmospheric-fried potato chips had lower moisture contents than vacuum-fried potato chips though the differences were not significant. Other than the treatment where fish sticks were vacuum-fried at 120°C, the core moisture content distributions were similar (Figure 4.6). The crust moisture distribution can be seen in Figure 4.7. While the distributions of crust moisture contents of treatments fried at 101 kPa were similar to each other, and so were those fried at 163 kPa, the two vacuum-fried (41 kPa) treatments' distributions were very different. The large variation in the distribution of treatment 5 (vacuum-frying at 150°C) made it difficult to determine the true effect that vacuum-frying had on moisture content. Perhaps a larger sample size could have reduced this variation, or it could be due to the natural variability association with the frying process.

Effect of Pressure on Oil Content

Treatment conditions did not have a significant effect on crust oil content ($p > 0.05$), while they did have a significant effect on core oil content ($p < 0.05$). Fish sticks vacuum-fried at 150°C had the highest core (5.86%) and crust oil contents (19.80%) (Table 4.3), though they were not significantly different ($p < 0.05$) from the pressure-fried treatments, in the case of core oil content, and the pressure-fried and atmospherically-fried treatments, in the case of crust oil content. Atmospheric-frying gave significantly lower core oil contents (3.08% at 175°C, 2.06% at 190°C) than the other frying methods, which can be seen clearly in Figure 4.8. Atmospheric-frying was next behind vacuum-frying at 150°C for the highest crust oil contents (19.61% at 175°C, 19.02% at 190°C). These results were opposite of what was expected. In a study done by Garayo and Moreira (2002), it was shown that vacuum-fried potato chips had a 13% lower final oil content than atmospherically-fried potato chips. Higher oil temperatures during frying speeds up crust development, thus providing surface properties that encourage oil absorption (Baumann and Escher, 1995). Vacuum-frying, with the low temperatures involved, should have led to the lowest oil contents. The variation in the 150°C vacuum-frying crust oil content data (Treatment 5 in Figure 4.9) might account for this disparity.

Another possible reason for these surprising results is the design of the vacuum fryer used in this research. Garayo and Moreira (2002) found that during the vacuum frying of potato chips, the majority of oil uptake was prevented during the pressurization period. In their research, the pressurization period took place while the fryer was being vented after potato chips were removed from the oil. During this period, as the pressure in the pores of the potato chips increased toward atmospheric level, both air and oil were carried into the empty pores. Because of the low pressures, gas diffused more quickly into the pores than the oil, inhibiting the oil's entrance into the pores. Because of the design of the vacuum fryer used in this research, products were still surrounded by oil during the pressurization period. No air was present to prevent the oil from rushing into the pores. In fact, the increasing the pressure from vacuum to atmospheric levels while products were still surrounded by oil might have enhanced the oil uptake, which would explain the high crust oil content of the fish sticks vacuum-fried at 150°C.

Fish sticks fried under vacuum (41 kPa) at 120°C had the lowest mean crust oil content (14.93%). This was not significantly different ($p > 0.05$) from the crust oil contents of fish sticks fried under atmospheric conditions (101 kPa) at 190°C (19.02%) or under traditional pressure conditions (163 kPa) at both 175°C (16.40%) and 190°C (16.08%).

Since the products vacuum-fried at 120°C were not fully cooked, the internal moisture did not migrate out of the product, leaving no room for oil to enter.

Effect of Pressure on Texture

Atmospheric frying gave the highest peak load, energy to peak load, and energy to failure point values (Table 4.4), demonstrating that products fried under atmospheric conditions were harder and tougher than those of all other treatments. Vacuum-frying gave the lowest peak load and energy to peak load values. Vacuum-frying at 120°C also gave the lowest energy to failure point values, probably because these fish sticks were uncooked and had very little crust formation. These results agree with those of Garayo and Moreira (2002) regarding vacuum-frying of potato chips. The vacuum-fried potato chips were softer than atmospheric-fried potato chips, though not significantly so. In Figures 4.10 and 4.11, the clear delineation between pressures, as they affect peak load and energy to peak load, can be seen. It's apparent that pressure affects texture of fried fish sticks. Atmospheric pressure was the only pressure to have a clear effect on energy to failure point, as can be seen in Figure 4.12.

CONCLUSIONS

Excluding the uncooked treatment (vacuum-frying at 120°C), vacuum-frying did not have any significant effect compared to pressure-frying in terms of oil content, moisture content, color, or texture. Vacuum-frying did create juicier fish sticks than the other two treatments. Vacuum-fried fish sticks were more tender than those fried at atmospheric pressure. The vacuum-fried fish sticks also had the highest core and crust oil contents, even though the difference was not significant. The vacuum fryer developed during this project effectively produced juicy and tender golden-brown fish sticks;

however, the design did appear to encourage, rather than inhibit, oil absorption. The fish sticks vacuum-fried at 120°C were not fully cooked. Therefore, further investigation is needed to determine proper time, temperature and pressure combinations for the vacuum-frying of breaded fried foods.

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Table 4.1 Effect of Pressure and Temperature on Crust Color of Breaded Fried Fish Sticks

	Treatment Means					
Color	Pressure (163 kPa)		Atmospheric (101 kPa)		Vacuum (41 kPa)	
	175°C	190°C	175°C	190°C	120°C	150°C
L*	100.404^{a}	79.411^{c}	$99.339^{a,b}$	82.962^{c}	$97.169^{a,b}$	$89.136^{b,c}$
a*	-1.259^{b}	8.659^{a}	0.987^{b}	7.310^{a}	0.767^{b}	1.216^{b}
b*	5.258^{a}	7.912^{a}	1.596^{a}	14.744^{a}	7.180^{a}	9.216^{a}

Treatment means that are not significantly different ($p > 0.05$) within rows have the same exponent.

Table 4.2 Effect of Pressure and Temperature on Juiciness of Breaded Fried Fish Sticks

	Treatment Means					
	Pressure (163 kPa)		Atmospheric (101 kPa)		Vacuum (41 kPa)	
	175°C	190°C	175°C	190°C	120°C	150°C
Juiciness (%)	30.01^{b}	32.93^{b}	31.56^{b}	29.38^{b}	43.03^{a}	41.31^{a}

Treatment means that are not significantly different ($p > 0.05$) within rows have the same exponent.

Table 4.3 Effect of Pressure and Temperature on Moisture and Oil Contents of Breaded Fried Fish Sticks

	Treatment Means					
	Pressure (163 kPa)		Atmospheric (101 kPa)		Vacuum (41 kPa)	
	175°C	190°C	175°C	190°C	120°C	150°C
Core MC (%)	67.18^{b}	68.82^{b}	65.20^{b}	67.01^{b}	74.20^{a}	67.48^{b}
Crust MC (%)	$39.03^{a,b}$	35.28^{b}	26.65^{c}	26.15^{c}	45.07^{a}	36.67^{b}
Core OC (%)	5.31^{a}	$4.58^{a,b}$	$3.08^{b,c}$	2.06^{c}	$4.32^{a,b}$	5.86^{a}
Crust OC (%)	$16.40^{a,b}$	$16.08^{a,b}$	19.61^{a}	$19.02^{a,b}$	14.93^{b}	19.80^{a}

Treatment means that are not significantly different ($p > 0.05$) within rows have the same exponent.
MC=Moisture Content, OC=Oil Content

Table 4.4 Effect of Pressure and Temperature on Texture of Breaded Fried Fish Sticks

Texture	Treatment Means					
	Pressure (163 kPa)		Atmospheric (101 kPa)		Vacuum (41 kPa)	
	175°C	190°C	175°C	190°C	120°C	150°C
Peak Load (kN/kg)	27.91^{a}	31.36^{a}	48.14^{b}	44.29^{b}	12.68^{c}	$23.49^{a,c}$
Energy to Peak Load (J/kg)	128.78^{b}	133.83^{b}	219.35^{a}	209.86^{a}	51.13^{c}	102.75^{b}
Energy to Failure Point (J/m^3)	1922.0^{b}	$1436.3^{b,c}$	3135.1^{a}	2869.6^{a}	1018.4^{c}	1706.8^{b}

Treatment means that are not significantly different ($p > 0.05$) within rows have the same exponent.

Figure 4.1 Vacuubrand Vacuum Pump used in this research

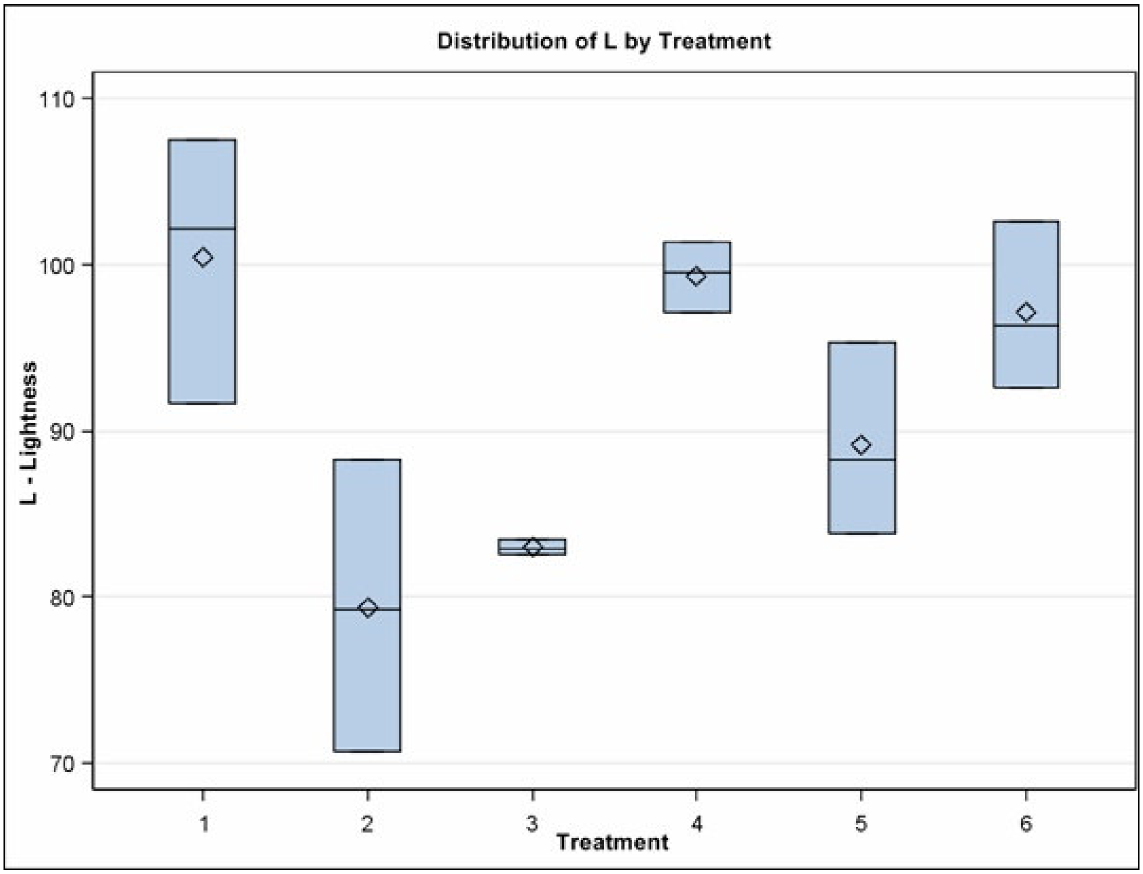

Figure 4.2 Distribution of L* by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

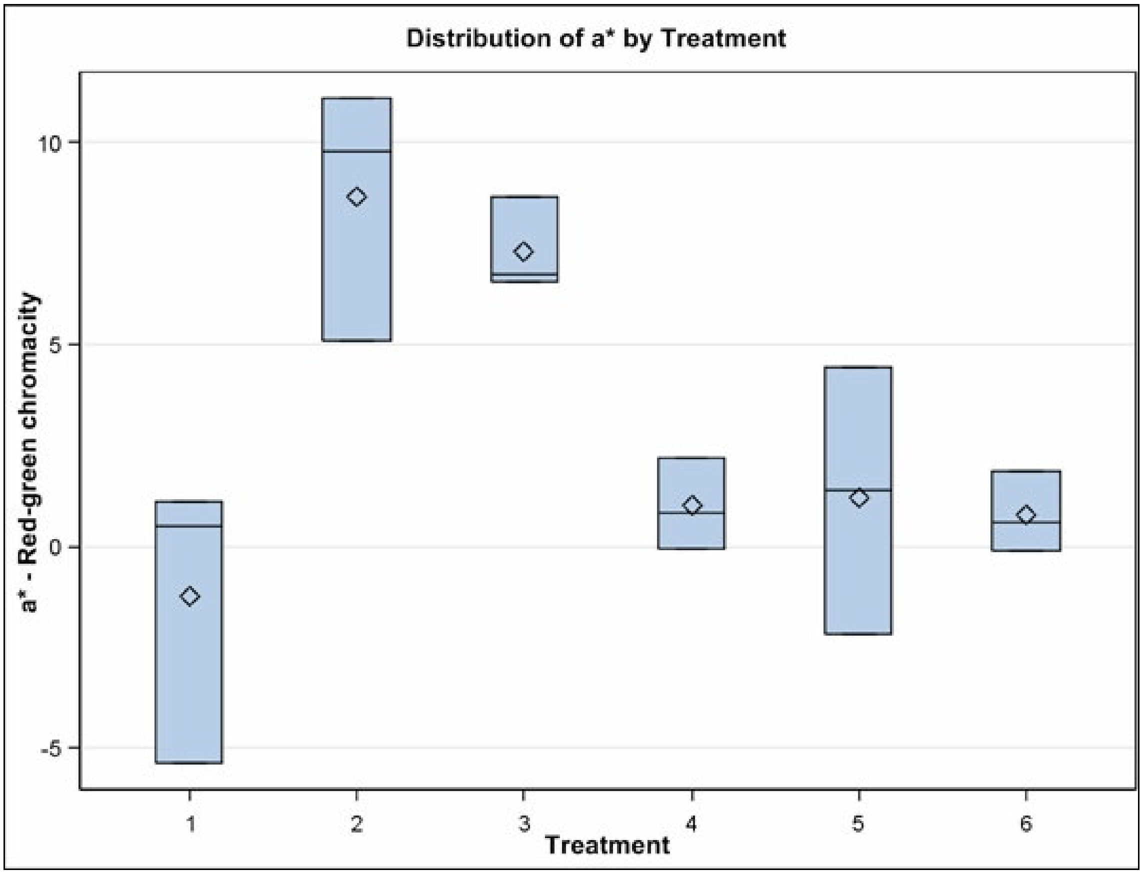

Figure 4.3 Distribution of a* by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

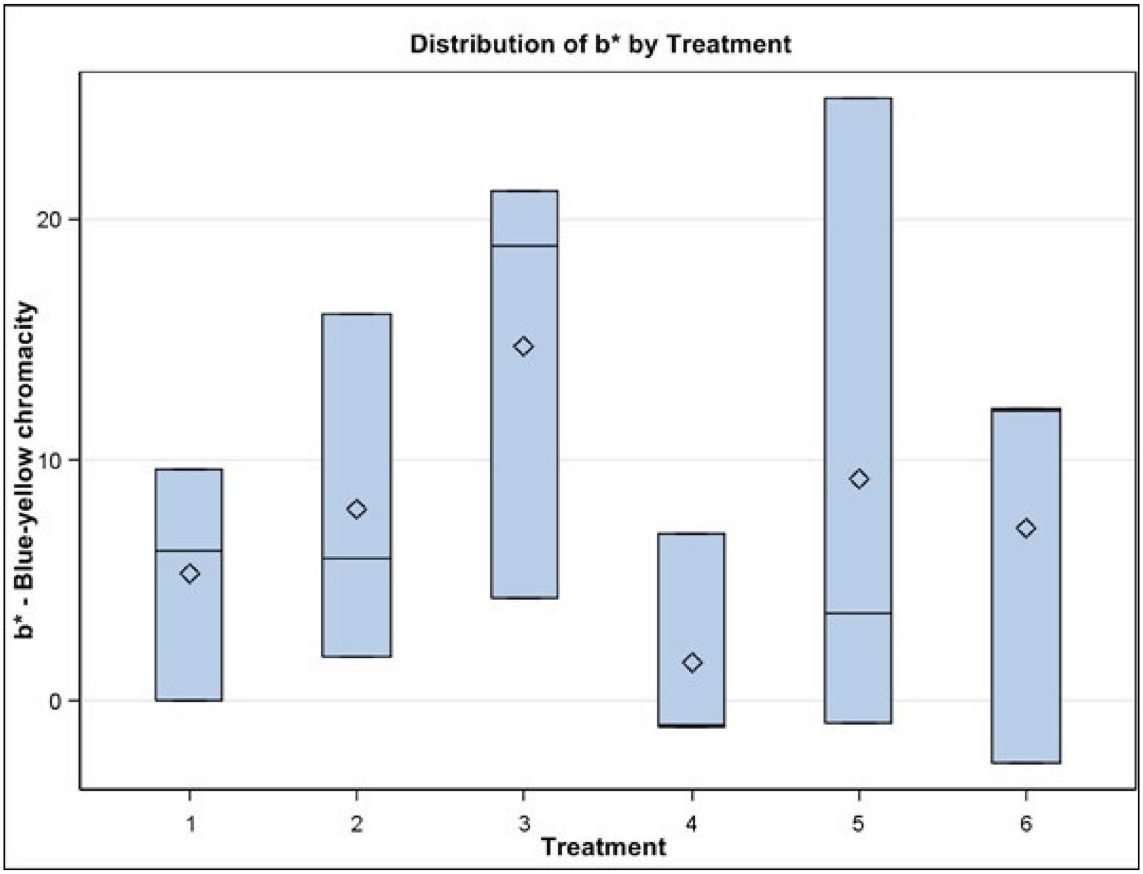

Figure 4.4 Distribution of b* by Treatment

1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

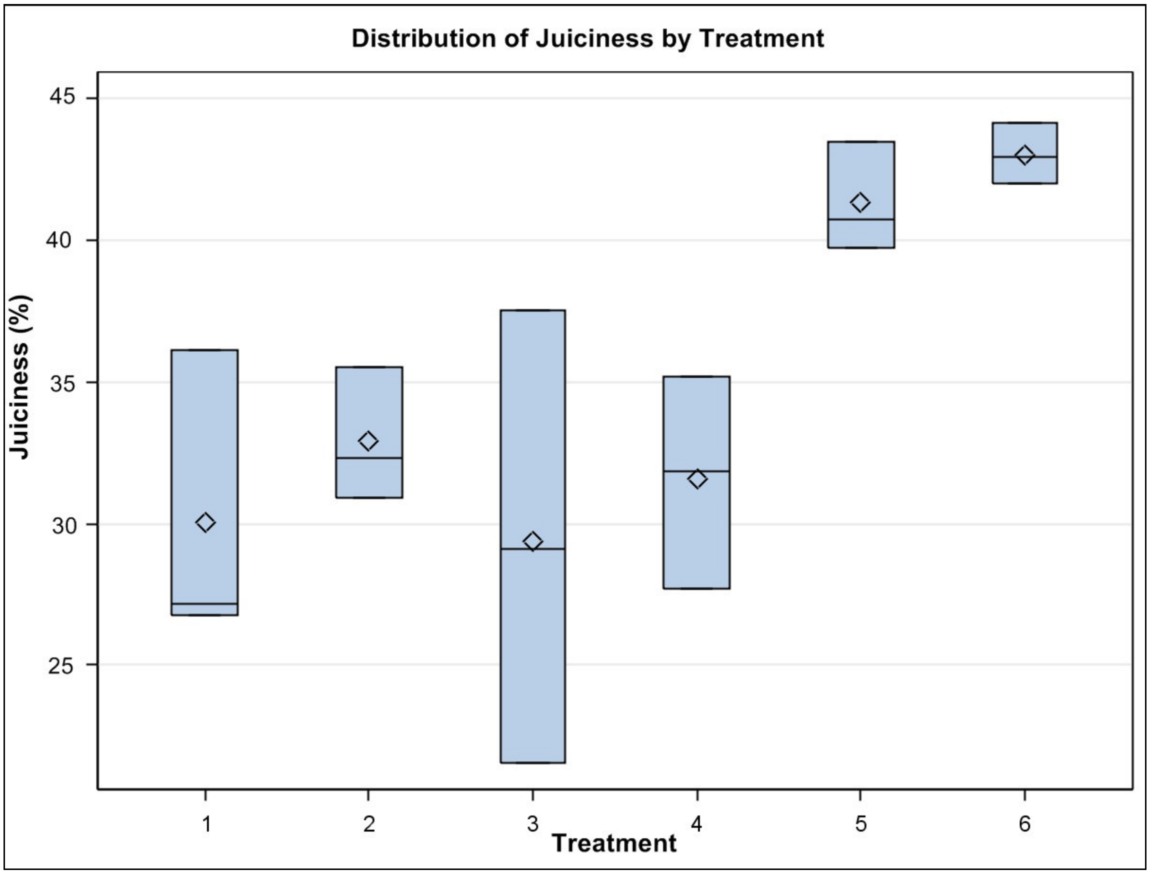

Figure 4.5 Distribution of Juiciness by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

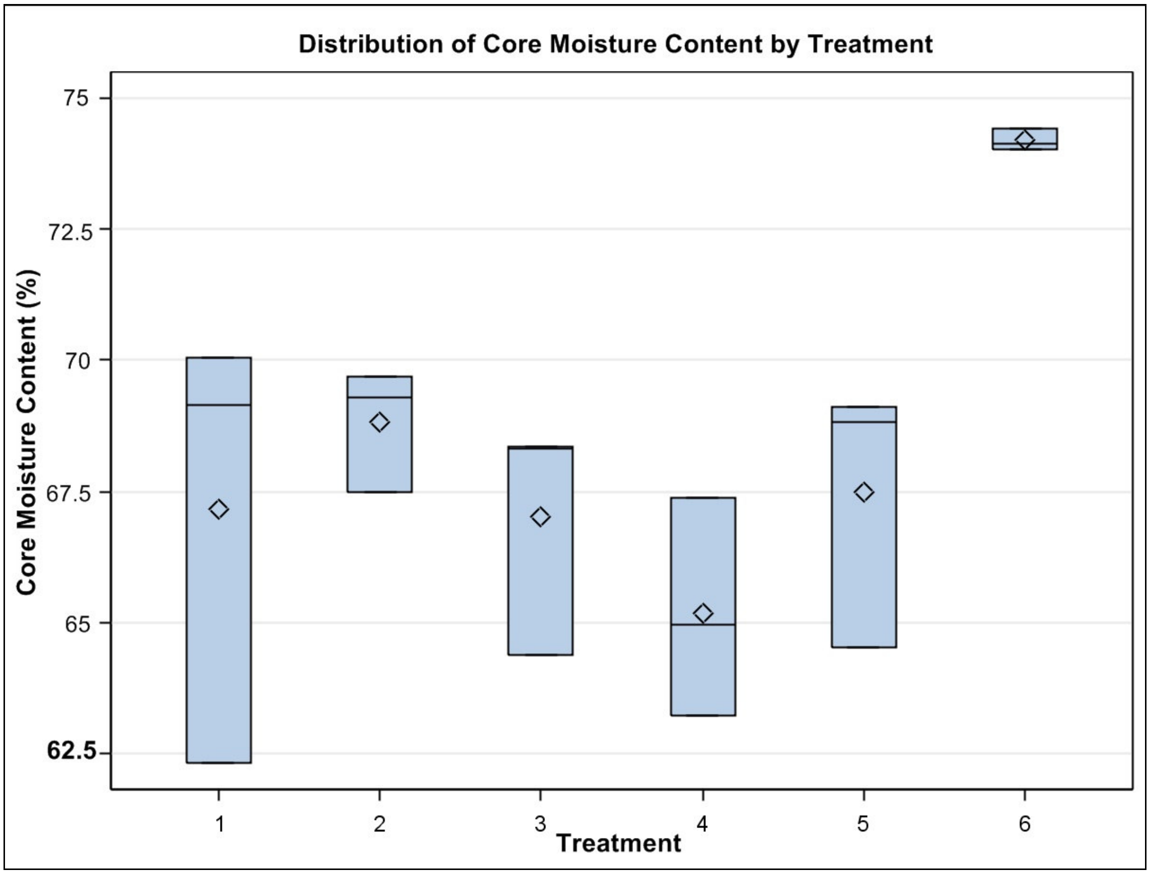

Figure 4.6 Distribution of Core Moisture Content by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

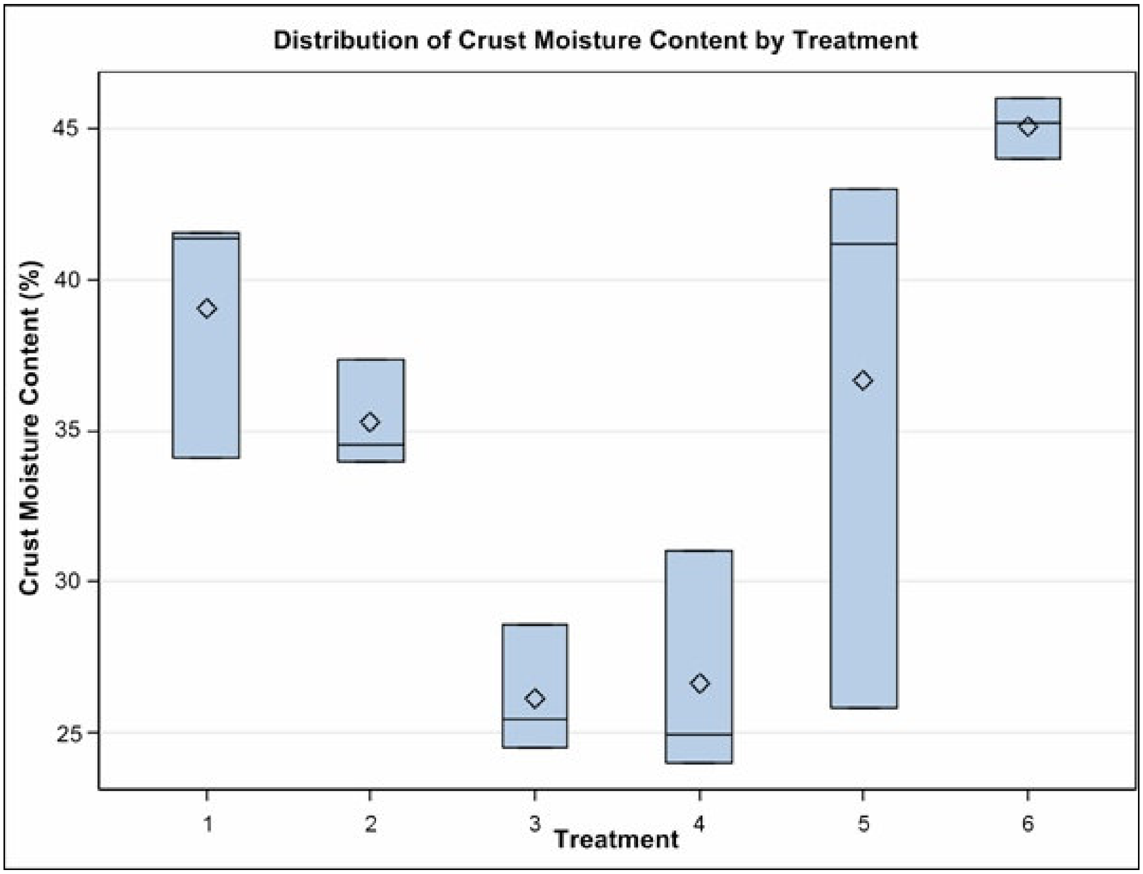

Figure 4.7 Distribution of Crust Moisture Content by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

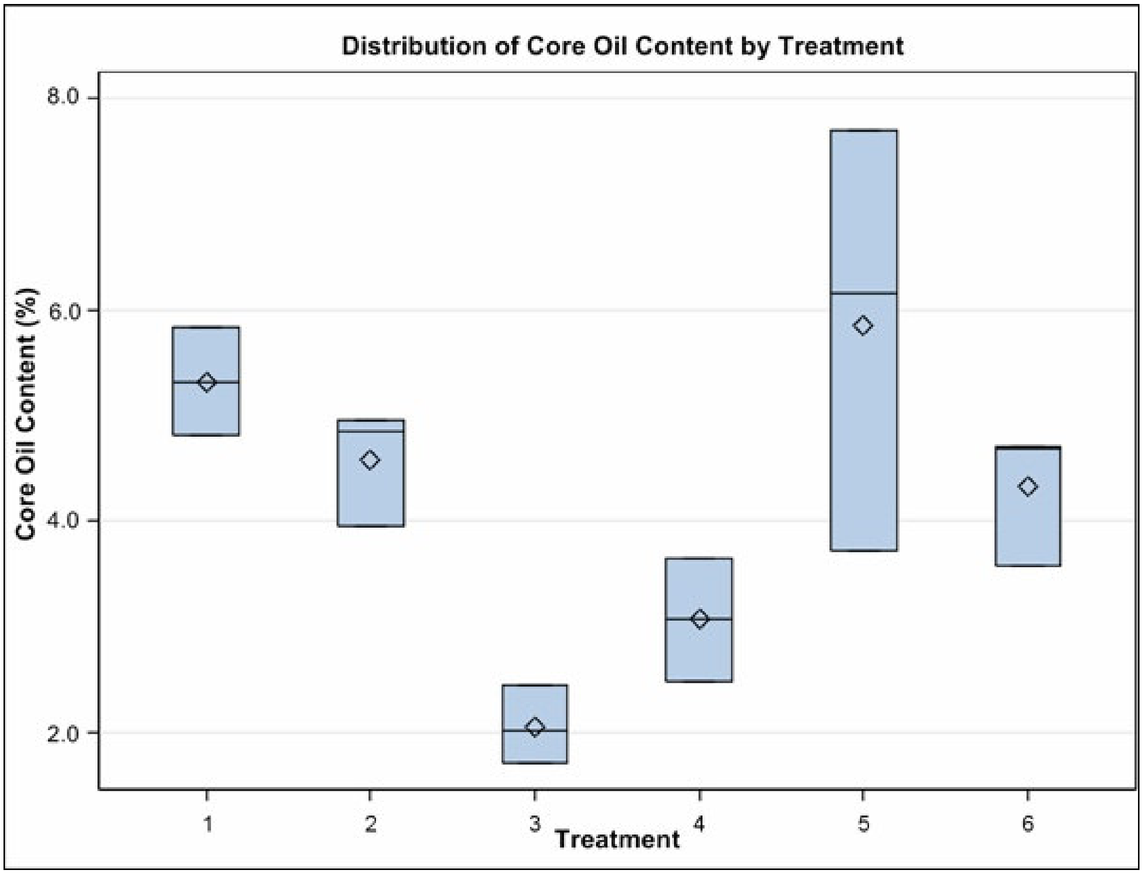

Figure 4.8 Distribution of Core Oil Content by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

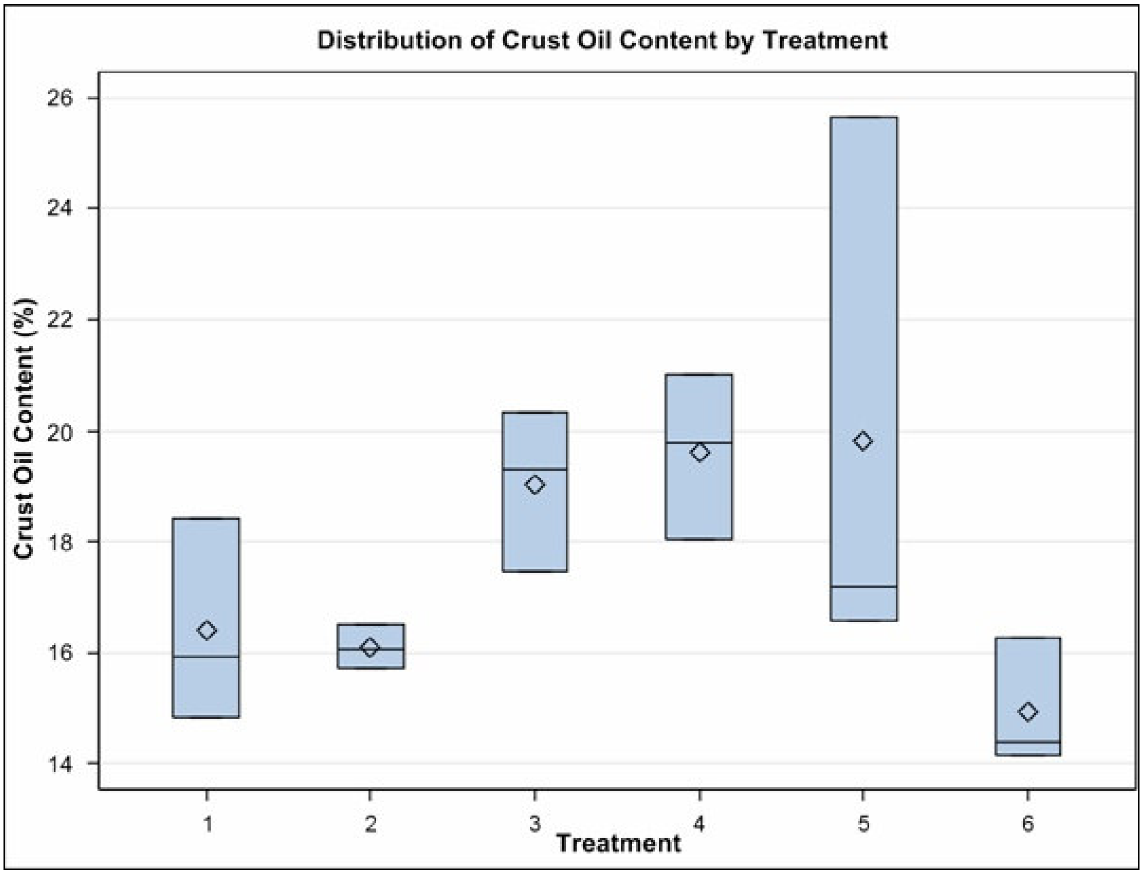

Figure 4.9 Distribution of Crust Oil Content by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

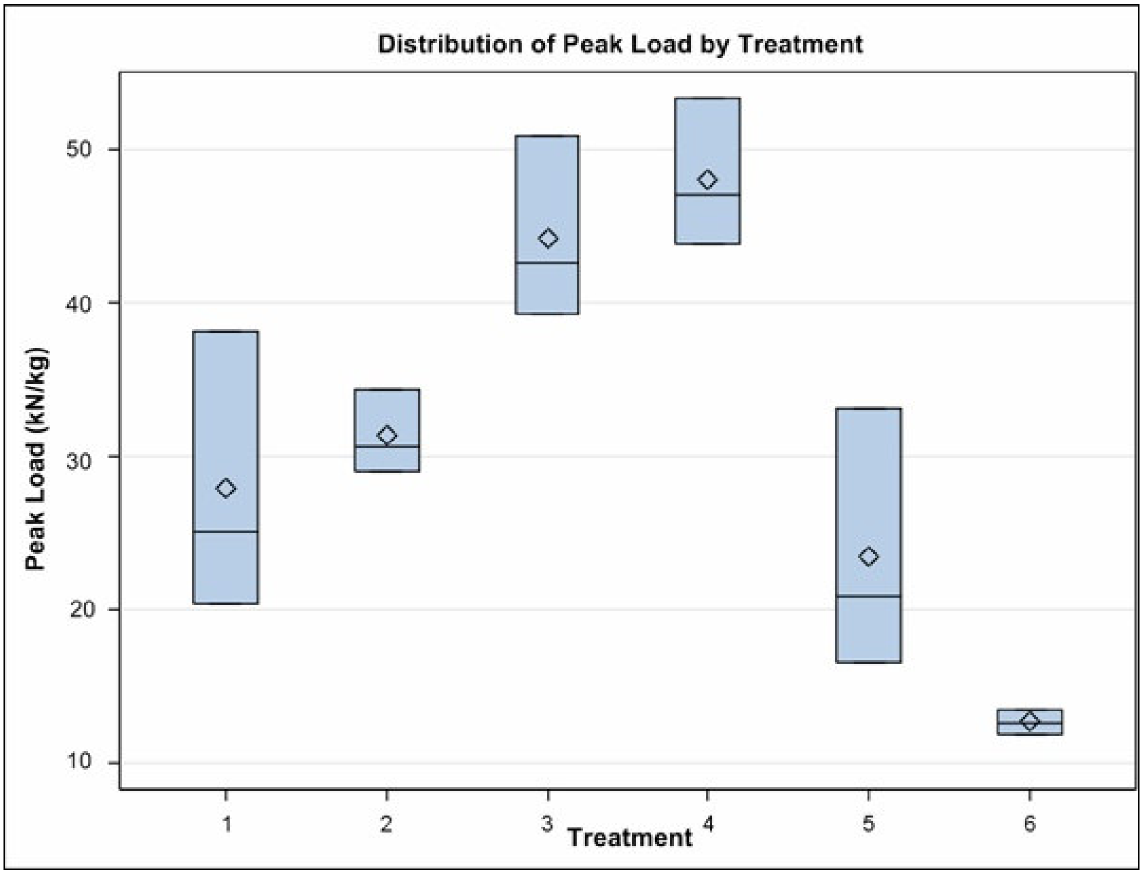

Figure 4.10 Distribution of Peak Load by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

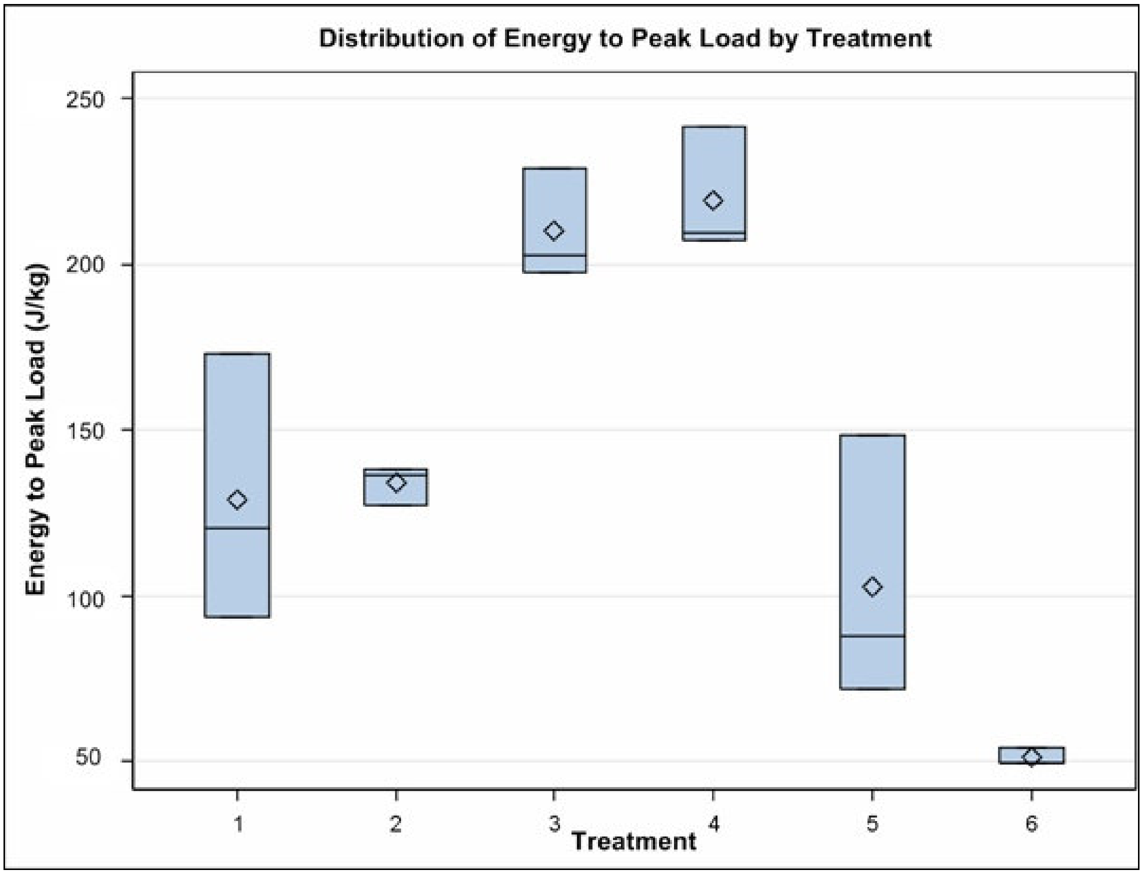

Figure 4.11 Distribution of Energy to Peak Load by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

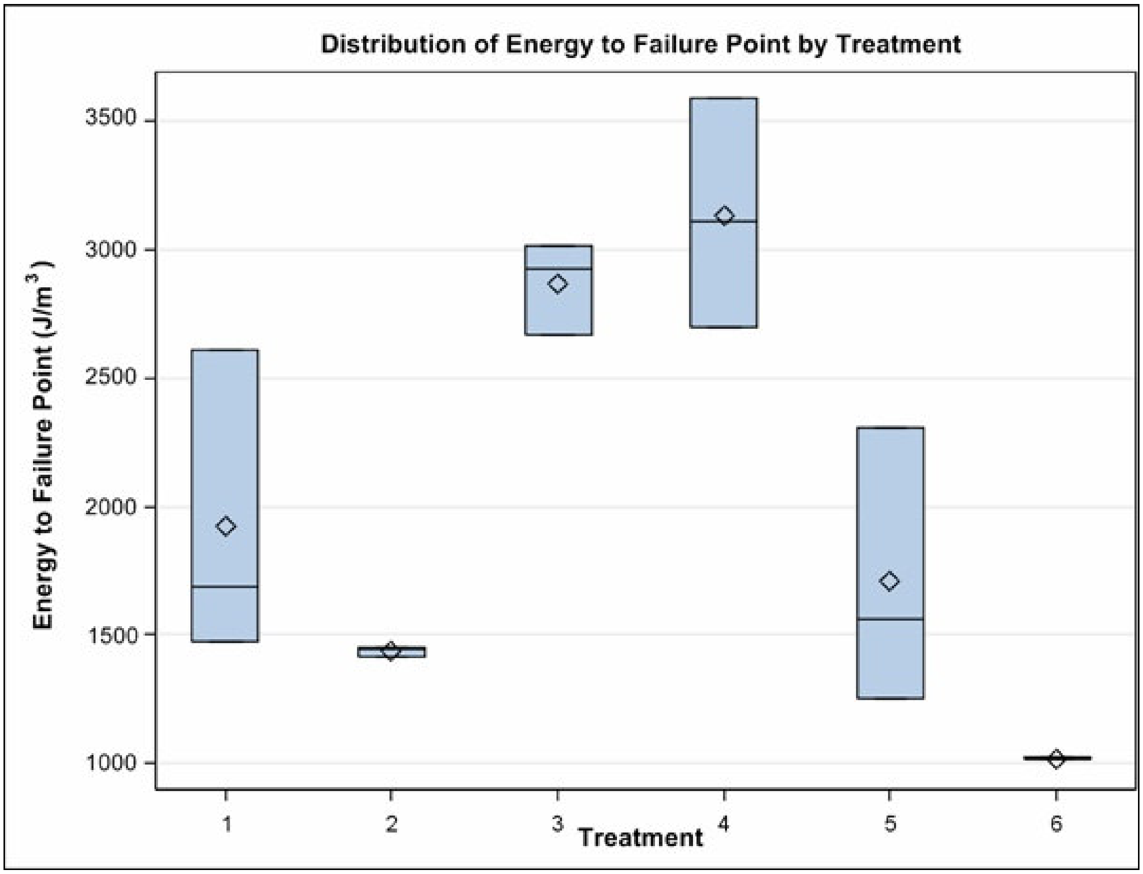

Figure 4.12 Distribution of Energy to Failure Point by Treatment
1 = 163 kPa, 175°C; 2 = 163 kPa, 190°C; 3 = 101 kPa, 190°C; 4 = 101 kPa, 175°C;
5 = 41 kPa, 150°C; 6 = 41 kPa, 120°C

CHAPTER 5

SUMMARY AND CONCLUSIONS

In the first study, the use of compressed air as a pressurizing medium was evaluated. Fish sticks fried in this way were compared to fish sticks fried using traditional pressure frying and using nitrogen gas as the pressurizing medium in terms of crust color, crust and core moisture and oil contents, juiciness, and texture. With the exception of core moisture content, where air (70.47% moisture by weight) gave significantly higher values than nitrogen (67.86% moisture by weight), there were no differences between the use of nitrogen as a pressurizing medium and compressed air. Fish sticks fried using air and nitrogen were more tender and had lower oil contents than those fried using traditional pressure frying. The mean crust oil contents of fish sticks fried using air and nitrogen were 17.35% and 15.88% oil by weight, respectively. The mean crust oil content of traditionally pressure-fried fish sticks was 23.31%. There was a 25% reduction in oil content between the traditionally pressure-fried fish sticks and those fried with air as the pressurizing media. Previous research has found that using nitrogen gas as a pressurizing medium increases the life of frying oil, but further studies should be done to explore the effect of air as a pressurizing medium on the life of frying oil, since it contains oxygen, which contributes to oil degradation. In addition, studies should be done that determine the effect of these novel methods on the quality of fish sticks that have been cooked to doneness, as opposed to being cooked for a constant time, as in this research.

In the second study, the use of vacuum-frying, or frying under reduced pressure, to cook breaded foods was explored. The quality of vacuum-fried (41 kPa) fish sticks was compared to the quality of fish sticks fried at atmospheric pressure (101 kPa) and at increased pressure (163 kPa) in terms of color, juiciness, core and crust moisture and oil contents, and texture. The vacuum fryer developed during this project was effective; however, since the fish sticks vacuum-fried at 120°C were not fully cooked (the internal temperature reached a maximum of 40°C), further investigation is needed to determine proper temperature and pressure combinations and correct cooking times for the vacuum-frying of breaded fried foods. Excluding the uncooked treatment, vacuum-frying did not have any significant effect on the oil content, moisture content, crust color, and texture of fish sticks, compared to pressure-frying. Vacuum-frying did create juicier fish sticks than frying under increased pressures. Vacuum-fried fish sticks were more tender than those fried at atmospheric pressure. Since there has been some success in the use of vacuum-frying to reduce the oil content of other fried products, and since vacuum-frying has been shown to increase frying oil life, further research is suggested to determine the suitability of vacuum-frying for cooking other breaded fried foods. In addition, studies should be done that assess the acceptability of vacuum-frying on foods that have been cooked to doneness, as opposed to being cooked for a constant time.

The effects of novel frying methods on quality attributes of fried fish sticks were compared to each other. There were no significant differences between vacuum frying at 150°C, frying with air at 163 kPa and 175°C, and frying with nitrogen with air at 163 kPa and 175°C, with the exception of crust oil content. Frying under vacuum led to a significantly higher ($p < 0.05$) mean crust oil content (26.35% oil by weight) than both frying with nitrogen (16.92%) and compressed air (16.29%). Sensory tests should be performed to assess consumer acceptance of fish sticks fried using the novel methods presented here.

The hypothesis of this research was that there would not be a significant difference between the use of air and nitrogen as pressure mediums during deep-fat frying. In addition, frying with air and nitrogen would give similar or better quality fried foods when compared to pressure frying. Finally, vacuum frying would create fried foods with reduced oil content when compared to pressure or atmospheric frying. Unexpectedly, air and nitrogen reduced the overall oil content of fried fish sticks, while vacuum-frying increased the oil content, compared to frying with pressurizing media. The differences between the use of air and nitrogen as pressurizing media, with the exception of core moisture content, were not significant. The results of this research demonstrated that novel frying methods could be used to fry fish sticks that were comparable in terms of quality attributes to fish sticks fried using atmospheric- and traditional pressure-frying.

VITA

Rhonda Bengtson was born on November 8, 1982 in Baton Rouge, LA. She received her Bachelor of Science in Chemical Engineering from Louisiana State University in May 2004. In August 2004, she entered Virginia Polytechnic Institute and State University to pursue a Master of Science in Biological Systems Engineering under the direction of Dr. P. Kumar Mallikarjunan. She completed the final exam for the degree in July 2006.