

Improving Fried Product and Frying Oil Quality Using Nitrogen Gas in A Pressure Frying System

Bhundit Innawong

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Kumar Mallikarjunan, Chair

John S. Cundiff

C. Gene Haugh

Joseph E. Marcy

George J. Flick

James H. Wilson

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By

Bhundit Innawong

ABSTRACT

The commercial pressure frying has been limited to frying huge amount of products due to its dependence on the amount of moisture released from the food for generating the desired pressure. This study investigated the feasibility of using nitrogen gas as a substitute for steam in the pressure frying system. The effects of various process conditions (source of pressure, frying temperature and pressure) on fried product and frying oil qualities were evaluated. Frying experiments were performed on breaded/battered poultry products including chicken nuggets (homogenous) and chicken fillets (marinated, intact muscle). Efforts were also made to develop rapid methods to determine frying oil quality and discriminate among fresh, marginal and discarded oils using a chemosensory (also known as electronic nose) or Fourier transform infrared spectroscopy (FTIR-ATR).

Frying temperature and pressure affected fried food quality. An increase in frying pressure resulted in tender, juicier products with less oil uptake due to high moisture retention. An increase in frying oil temperature resulted in an increased moisture loss, oil uptake resulting in less tender and juicier products. Compared with frying using steam released from food, using nitrogen provided similar or better quality fried products in terms of moisture retention, juiciness and texture. The reused oils from the fryer using nitrogen gas was better in quality than the system using steam as evidenced from the physical, chemical and chemosensory measurements.

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CHAPTER 1

INTRODUCTION

Although the trend in North America is toward lowering fat consumption, frying still represents a product of high demand, and frying oil consumption is measured in million pounds per year. The development of both industrial and food service frying equipment led to an increase in variety of fried foods for the American diet.

Deep fat frying is one of the widely used processes for cooking foods. The essential requirements are to divide the food into uniform portions, apply a breading or batter, if appropriate, and then fry. After the frying time and temperature have been set for a given product, production becomes completely routine. In the United States, fried food is a multibillion-dollar industry and most food service operations rely heavily upon deep fat frying for cooking french fries (potato crisps), poultry, meat, seafood, and vegetables.

The popularity of deep fried products is due to the basic structure imposed on them by the way in which they are cooked (Stevenson et al., 1984). The soft and moist interior along with the porous outer crispy crust in fried foods provides increased palatability (Orthofer et al., 1996; Varela, 1988). The key attributes of deep fat frying are high temperature, rapid heat transfer, and absorption of some frying oil. The oil provides an effective medium for energy transfer from the heat source to the food (Orthofer et al., 1996). The process generates foods that are a pleasure to eat with crispy texture, rich flavors and aromas. Various chemical reactions involving amino acids, proteins, and carbohydrates account for much of the flavor of fried foods.

Having an attractive and tasty product surface, deep fat frying is a widely used thermal processing method. Many researchers have studied the relationship between oil uptake and moisture loss during frying. The oil absorption into the product during deep fat frying is influenced by: oil temperature (Guillaumin, 1988), frying time and surface moisture content (Lamberg et al., 1990), product surface area (Gamble and Rice, 1988), pressure (Roa and Delaney, 1995, Mallikarjunan et al., 1997), and frying oil quality (Tseng et al., 1994). The quality of the oil used in deep fat frying contributes to the

quality of the fried food. The quality of the frying oil and of the food fried in that oil are intimately related (Blumenthal, 1991). Frying oil quality influences oil absorption and the types of by-products and residues absorbed by food. The type of food being fried influences frying oil life.

Oil is a significant cost in the deep fat frying of foods. Repeated use of frying oil produces constituents that may pose health hazards leading to quality and economic loss to the processor. The deterioration of frying oils is familiar to all users of frying oils. Reduction in oil quality results in fried foods that are improperly browned or that have unappealing flavor (Perkins, 1992). There are several factors that influence the quality of the frying medium, including air exposure, steam or moisture exposure, stability of the oil to oxidation, contamination of the frying oil with the fat extracted from the food being fried in it, and contamination from charred food particles primarily from the breading mixes used to coat fried foods (Orthoefer, 1988).

The type of food being fried and variation of breading mixtures and its interaction with oil also may contribute to the deterioration of frying oil (Holownia et al., 1999). Deterioration of frying oil generally characterized by changes in free fatty acid level, color, or an increase in polarity of the oil (Melton et al., 1994; Orthoefer et al., 1996; Paradis and Nawar, 1981; Tan et al., 1985; White, 1991). Recently, the fast food industry is adapting various methods of maintaining the quality and increasing the useful life of frying oil (Paul and Mittal, 1997). They include the use of active and passive filters, antioxidants, and proper maintenance of the fryer equipment (Lin et al., 1998; Orthoefer, 1988; Rhee et al., 1992). In addition, they are also trying to limit the oil uptake in fried foods (Jacobson, 1991).

Frying food products under pressure is known to yield more juicy and tender products than atmospheric pressure. By suitably selecting pressure and temperature, consumer desired characteristics can be obtained in the end product. Though this knowledge is known, much of the information is under proprietary patented documents. Thus, various parameters for optimum processing for any type of food product are not available. This limits the use of this technology to a very few food products for which a method has been established. In addition, the existing pressure frying equipment relies on the moisture released from the products to generate the pressure. The moisture

released from the products mixed with the air can deteriorate the oil faster. As this method relies on the amount of moisture/steam released from the food for pressure, the use of this equipment is also limited to a situation where a large load is fried.

To develop a pressure frying method that does not depend on the product load, the objective of this study was to use nitrogen gas to generate the required pressure in the fryer instead of using steam generated from the moisture of the products. The primary focus of this study was to evaluate the effect of nitrogen gas on fried product quality and frying oil quality during pressure frying of breaded food products and to characterize the moisture retention and reduction in lipid uptake in fried foods as influenced by frying temperature, pressure, and the source of pressure generation during deep fat frying of several breaded fried poultry products such as chicken nuggets and chicken fillets.

CHAPTER 2

LITERATURE REVIEW

Deep fat frying of foods is considered everywhere in the world to be the most common unit operation used in food preparation. Therefore, to produce, preserve, and market fried food optimally, it is essential to understand the frying mechanism, the factors affecting the oil uptake, and the changes of frying oil during frying. In addition, this chapter briefly introduces the measurements of oil quality used widely in the frying industries.

2.1 Frying Process

Frying, considered as one of the oldest cooking methods in existence, originated and developed in the olive growing countries due to the availability of olive oil (Varela, 1988). Nearly every restaurant, fast food institution, most bakeries, and supermarkets provide deep fat fried products. In the United States, the snack food business continues to grow every year. Deep fat frying is commonly used in the multimillion-dollar snack industry.

Deep fat frying is a very popular and widely utilized in food preparation because it is fast and convenient. Frying is still considered to be more an art than a science because it is an extraordinarily complex process involving various factors; some of which are dependent on the process itself and others on the food and the types of frying medium used.

Deep fat frying involves cooking foods by immersing them in hot oil. Frying oil functions primarily as a heat-conducting medium for the food. This increases the temperature and causes the food to cook. The optimum deep fat frying temperature for coated food ranges from 175°C to 205°C (or 350°F to 400°F). Rapid heat transfer quickly sets the coating structure, allowing little time for excess moisture infiltration (Kulp and Loewe, 1996). Frying produces unique desirable attributes in foods. These attributes include crust formation, unique flavor and aroma, and golden color of the product.

Frying exhibits a similar loss of moisture as in a classical drying profile (Gamble et al., 1987). Oil from the heating medium is absorbed by the food and parts of foods disintegrate and get deposited into the oil. In the process of frying, the food product undergoes various complex changes. The major changes in chemical and physical properties include starch gelatinization, protein denaturation, water vaporization, and crust formation (Saguy and Pinthus, 1995).

2.2 Frying Mechanism

Deep fat frying is defined as a classical process of cooking and drying food through contact with hot oil and it involves simultaneous heat and mass transfer (Moreira et al., 1995). Heat is transferred from the oil to the food product, moisture is evaporated from the product, and finally, the product absorbs oil. The simultaneous appearance of both heat and mass transfer makes the theoretical treatment more complicated because the physical properties of food materials vary with the changes in temperature and moisture content (Sahin et al., 1999). Moreira et al. (1995) suggested that factors affecting heat and mass transfer are the thermal and physical properties of the food and the oil, the geometry of the food, the temperature of the oil, and the frying conditions that will lead to the degradation of the oil. Blumenthal (1991) presented a comprehensive model of a water-laden sponge to describe the complex mass and heat transfer phenomena involved. He also reported that a water-laden sponge might be used as an analog system for the food undergoing frying. The sponge has an interior volume, edges, walls, and a uniform distribution of water in an evenly divided matrix of cells. In addition, the simplest real life analogy to this idealized model system is a potato crisp, which will be used as a model food undergoing frying.

In a systematic study of heat transfer during frying, water plays a variety of roles to transfer heat into the sponge. It carries off thermal energy from the hot frying oil surrounding the frying food. This removal of energy from the surface of foods can prevent charring and burning caused by excessive dehydration. In addition, the evaporation of water as in the form of steam escaping from the foods also carries off the bulk of the contacting oil's energy. As long as the water is leaving, the surface of food

will not char or burn. From this reason, although the frying oil temperature may be 180°C or more, the temperature of fried food is only approximately 100°C representing the temperature of phase change of water (Blumenthal, 1991). However, in the actual food system, the boiling point of water is elevated due to the presence of solutes in the system.

Normally, the temperature inside the food is restricted to values below the boiling point of liquid. During the frying process, the removal of water from the outer regions of food material continues. Consequently, the temperature of dried regions (crust) starts to rise slightly above the boiling point (Singh, 1995).

Mass transfer during deep fat frying is characterized by the movement of oil into the food, the movement of water vapor from the food into the oil (Singh, 1995), the movement of fat from the food into the oil (Mallikarjunan et al., 1995). During the dehydrating phase of frying, water migrates from the interior portion of the product to replace that is lost by dehydration at the exterior surfaces. While water is moving to the exterior, an opposite diffusion begins to take place where the voids left behind by the water and the foods begin to absorb oil via inward mass diffusion. Thus, an understanding of the complex processes occurring during deep fat frying is essential to control the quality of the final fried products. Mathematical modeling provides a tool to study the effect of processing conditions in deep fat frying of foods. In addition, quantitative information can be used to describe the rate of heating, oil penetration into the food, oil-food interactions, and texture development during deep fat frying (Singh, 1995).

2.2.1 Heat Transfer

There are two distinct modes of heat transfer taking place during frying: conduction and convection. Conductive heat transfer occurs within the solid food. The rate of heat transfer is influenced by the thermal properties of the food, including thermal conductivity, specific heat, and density. Convective heat transfer occurs between a solid food and the surrounding oil. Water plays an important role in the convective heat transfer. The surface interactions between the oil and the food material are complicated

because of the vigorous movement of water bubbles escaping from the food into the oil (Singh, 1995). Singh (1995) also reported that the water vapor bubbles escaping from the surface of the food cause considerable turbulence in the oil. In addition, the water vapor bubbles entrapped on the underside of the food material prevent efficient heat transfer between the bottom side of the food and the oil. If the food object floats near the top of the oil bath, then the oil foam significantly alters the rate of heat transfer to the top surface of the food (Levine, 1990a,b). The amount of water vapor bubbles escaping a food material decreases with an increase in frying time as a result of the decrease in the remaining moisture in the material.

The main function of the frying oil is to provide heat to the food being fried. Temperature of the frying oil is usually maintained well above the boiling point of water. Heat transfer in the frying oil from the heating element is through convection. At the surface of the food, heat from the frying oil is transferred through conduction into the food. Subsurface water also facilitates the conduction of heat energy through surfaces that came in contact with the oil (Blumenthal, 1991). The rate of heat transfer is increased by the absorption of the hot oil into the food. Heat conducted by the frying oil converts water into steam. The steam evaporates as bubbles that commonly observed when foods are fried.

Due to the evaporation, the temperature of the food during frying remains below the boiling point of liquid. The liquid inside the food contains some solutes, thus the boiling point is slightly higher than the boiling point of water. The temperature increases above the boiling point as more water evaporates (Singh, 1995). Balasubramaniam et al. (1997) in monitoring the temperature of chicken nuggets during deep fat frying observed a rapid increase in temperature at the surface to a point slightly above 100°C after 75 seconds. The temperature then remains constant up to 125 seconds of frying from which onwards it increases until the end of frying.

The driving force for the heat transfer process is the difference between the temperature of the oil and boiling point of liquid (Levine, 1990b). To transfer heat, the driving force must overcome two resistances, the oil film on the surface of the food and the crust layer that has poor thermal conductivity. After a short time of frying, about a second, the oil film does not normally present a significant heat transfer resistance

because the oil film is very thin caused by the turbulence of air and water escaping from the food (Levine, 1990a).

Farkas (1994) developed a predictive heat transfer model in a moving boundary problem in potato strip. Based on his observations, he suggested that the frying process is composed of four distinct stages:

1. Initial heating. The initial heating stage usually lasts a few seconds. The surface of a food submerged in oil heats to a temperature equivalent to the elevated boiling point of liquid, but no vaporization occurs from the surface of food during this stage. The mode of heat transfer between the oil and the food material is natural convection.
2. Surface boiling. The vaporization process begins the surface boiling stage and crust begins to form at the surface of food during this stage. The mode of convective heat transfer changes from natural to forced convection due to the presence of significant turbulence of oil surrounding the food material.
3. Falling rate. During this stage, more internal moisture moves outward from the food. The internal core temperature rises to the boiling point and several physicochemical changes such as starch gelatinization and cooking occur in the internal core region. The formation of crust continuously increases its thickness. In this stage, more removal of moisture (the vapor transfer) at the surface decreases.
4. Bubble end-point. After a considerably long period of time, the rate of moisture removed decreases and no more bubbles are seen escaping from the surface of the product. As the frying process proceeds, the crust layer continues to increase in thickness.

A fried food such as potato crisp commonly can be divided into three characteristic zones: the interface between food material and hot oil, the crust area, and the inner core (Guillaumin, 1988). The crust region contains a negligible amount of water, and its temperature is much higher than the boiling point of liquid. The properties of the crust are considered to be uniquely different from the core properties. The crust layer is golden brown in color and makes the fried food more unique and delicious. The development of color in this zone is actually the results of several chemical reactions

including caramelization or Maillard reaction. The core region can be characterized as being moist and soft.

2.2.2 Moisture Transfer

As a food material undergoes frying, heat transferred from the hot oil into the food causes several important chemical and physical changes such as starch gelatinization, protein denaturation, water vaporization, crust formation, and color and flavor development. Mass transfer during frying is characterized by the movement of oil into the food and the movement of water, in the form of vapor, from the food into the oil. Moisture evaporation occurs at the interface between the dry layer and undried core of the food (Levine, 1990a).

Various semi-empirical models have been developed for the rate of moisture loss and oil uptake. A variety of research has been done to propose the models describing moisture adsorption characteristics of the biological products, especially in the potato products. Past research on heat and mass transfer in frying has been limited to the formulation of empirical and semi-empirical equations. Ashkenazi et al. (1984) and Mittelman et al. (1984) proposed a semi-empirical relationship for heat and mass transfer during frying. It was found that for a model food (sponge) the moisture content of the product was proportional to the square root of frying time and the difference between the oil temperature and boiling temperature of water. Gamble et al. (1987) and Keller and Escher (1989) used the same model to describe the drying rate of potato products in deep fat frying. However, Keller and Escher (1989) modified the mathematical model proposed by Mittelman et al., (1984) for frying potato products with the addition of the term for the sensible heat required to heat the dry crust region from the boiling point of water to the oil temperature. Gamble et al. (1987) also suggested the mechanism based on potato slices for moisture transfer during deep fat frying. Slices for frying initially contained bound water and moisture released from slicing. When put into oil, this loosely held water evaporates and after a period of time all water is lost. Further water loss is only possible by movement from the interior of the product.

Kozempel et al. (1991) used the Fick's law of diffusion to model moisture loss and zero-order kinetics to predict the oil adsorption during deep fat frying of potato crisps. Frying experiments were conducted at oil temperatures of 185°C, 195°C, and 201°C using potato crisps with a minimum dimension of 1 cm. It was proposed that diffusivity was a function of oil temperature. Moreira et al. (1991) also used this diffusion model to predict moisture loss for tortilla chips during deep fat frying.

During frying, the diffusion gradient and pressure gradient force the steam towards the surface. Diffusion gradient is due to the existence of a dry surface while pressure gradient results from the inner moisture converting to steam. The steam finds selective weaknesses of the structure of the product and escapes. The amount of water vapor bubbles expelled from the food decreases over time due to the decreasing moisture content in the food (Singh, 1995). Balasubramaniam et al. (1997) reported a decrease in moisture content over time in chicken nuggets during deep fat frying. Both the surface and core portion of the chicken nuggets experienced a gradual decrease in moisture content. Throughout the frying process, rate of moisture loss was most rapid during the first 30 s of frying and reduced afterwards until the end of frying.

2.2.3 Crust Formation

As a result of the removal of moisture from food to the oil, the development of a dry layer, called crust, on the surface of the food gradually take places. Crust is one of the most palatable characteristics of fried food (Varela, 1988). The properties of the crust are uniquely different from the inner core because of containing relatively negligible amount of water/moisture compared to the core. In addition, the temperature of the crust is also higher than the boiling point of liquid (Singh, 1995). Levine (1990a) reported that the crust layer grows similar to the growth of the ice layer during freezing. Due to its dry and poorly conducting nature, the crust limits the rate of heat transfer (Levine, 1990b).

Before the formation of a crust layer of one millimeter thick, the rate of frying depends on the rate of heat able to be transferred into the food (Levine, 1990a). This results in the frying process being heat transfer limiting. As the crust is a poor conductor of heat, the rate of frying after approximately one millimeter of crust has formed depends

on the rate of moisture diffusion from the undried portion to the dried portion of the product. At this point it becomes mass transfer limiting (Levine, 1990b).

Oil uptake and the distribution of oil in the fried products occur mainly near the surface (Gamble et al., 1987; Keller et al., 1986). Thus, crust formation could be closely associated with oil distribution in the fried food (Varela, 1988). It was found that the oil tends to concentrate more near the edges, corners, and broken “slots” in the fried products. Polymers present in the frying oil are preferentially adsorbed on the crust surface and in the outer layers. This layer contains much more oxidized, polymerized, and carbonized oil fractions than the frying medium.

2.2.4 Oil Transfer

A comprehensive study of oil uptake and moisture loss in the frying potato chips reveals some interesting aspects of mass transfer. Gamble and Rice (1987, 1988) and Rice and Gamble (1989) reported that the oil content and the moisture content were directly related. The oil uptake and the moisture loss were expressed as a function of the square root of frying time. The total yield of the product decreased with frying time since the loss of moisture was more rapid than oil uptake. The distribution and the absorption of oil depended on several factors including the pre-drying treatment, frying time, surface area, and the thickness of the potato chips. In addition, a linear relationship between thickness of potato chips and the amount of oil absorbed was found (Guillaumin, 1988). Gamble et al. (1987) and Gamble and Rice (1988) reported that in frying potato slices 1.04-2.11 mm thick, the oil uptake was related to the surface area of the potato slices. The final oil content decreased linearly with increased thickness. They also proposed that the final oil content of the potato chip may be controlled by the thickness of slices.

Moreira et al. (1991) also reported that the distribution of the oil in tortilla chips was not uniform and that most of the oil easily concentrated around the edges and the puffed area of the chips. Several researchers have reported that the oil content in the product is independent of the frying temperature but closely related to the water content (Gamble et al., 1987; Pinthus and Saguy, 1994; Rice and Gamble, 1988;). Increased

frying temperature generally decreases oil uptake as a result of the reduction in the overall time in the fryer (Gamble et al., 1987).

During the oil absorption, capillary displacement could have played a major role (Pinthus and Saguy, 1994). Saguy and Pinthus (1995) proposed the mechanisms of moisture loss and oil absorption during deep fat frying and summarized as following: (1) high temperature creates “explosive” boiling of the water contained in the fried material, (2) this bursts cell walls and forms capillary holes and voids, (3) oil is absorbed into those holes and voids, and (4) oil uptake is increased by a reduction of internal pressure due to water loss and by subsequent cooling which creates a “vacuum effect”. It was further suggested that oil that enters the voids left by the moisture loss could maintain the capillaries open by keeping the structure from shrinking or collapsing; hence, moisture loss could be also affected by the amount of oil uptake.

Most of the work done on deep fat frying in relation to oil transfer has been limited to non-fatty foods such as potato products and tortilla chips. Few researchers have studied the mechanism of fat transport in initially fatty products such as meat and chicken products. Ateba and Mittal (1994) developed a modeling simulation of simultaneous fat, heat, and moisture transfer during deep fat frying of beef meatballs having an initial fat content. They proposed that fat transfer could be divided into two periods including fat adsorption and fat desorption. During fat absorption, fat is absorbed to the product surface in the space vacated by evaporated moisture. This phenomenon of fat replacing escaping moisture was also suggested by Guillaumin (1988). The mechanism of diffusion is similar to non-fatty foods. During the second stage, fat desorption occurs and the fat flowed from lower to higher concentration. Thus, fat from the product migrates into the frying oil through capillary flow. The pressure difference was thought to be the most probable reason for the fat desorption. The driving force was a tension gradient in the capillaries. This force is caused by the expansion of fat and shrinkage of the capillaries in the product probably due to collagen shrinkage and denaturation of meat proteins. Mallikarjunan et al. (1995) also reported similar absorption and desorption periods occurring at the surface of deep fat fried chicken nuggets.

2.3 Modeling of Deep Fat Frying

An understanding of the complex processes occurring during deep fat frying is necessary in order to control the quality of the final fried products. The modeling of deep fat frying can give quantitative information such as the rate of heating process, the rate of oil penetration into the food, the characteristic of oil-food interactions, the rate of oil degradation, and the texture development during frying. These are useful for food processors to monitor the undergoing process and control the quality of products.

Ashkenazi et al. (1984) and Gamble (1987) used a water diffusion model and found that the rate of moisture loss was proportional to the square root of frying time during frying of potato crisps. Rice and Gamble (1988) were able to model the loss of moisture during deep fat frying of potato slices. By using Fick's law of diffusion based on a slab, they found that the diffusion coefficient of moisture changes with frying oil temperature. The diffusion coefficient remains approximately constant between 60 s and 240 s followed by a rapid increase as frying time approaches 300 s.

Kozempel et al. (1991) used Fick's law of diffusion to model moisture loss and a zero-order rate equations to model oil uptake. Moreira et al. (1991) also used the diffusion model to predict moisture loss for tortilla chips during deep-fat frying.

Several studies have been done in simulating heat and mass transfer with successful results. Heat transfer is one of the most studied aspect in describing the deep fat frying. The food products that have been used include meatballs (Ateba and Mittal, 1994b), edible film coated chicken nuggets (Mallikarjunan et al., 1995), breaded chicken pieces (Roa and Delaney, 1995), and tortilla chips (Moreira et al., 1995). In all of the above studies, Fourier's law of heat transfer forms the basis for the models. All the models were able to predict the heat transfer profile of the various products.

Ateba and Mittal (1994) and Mallikarjunan et al. (1995) applied Fick's law of diffusion based on a one-dimensional mass transfer in a spherical geometry to predict fat, moisture transfer during deep fat frying. They also used Fick's law for the absorption phase and capillary flow for the desorption phase to simulate fat migration during deep fat frying. In diffusion theory, it is assumed that liquid moved through a solid body as a

result of a concentration gradient, while capillary theory assumes that the flow of liquid through the capillaries was caused by solid-liquid molecular attraction.

Roa and Delaney (1995) proposed that mathematical modeling of heat and mass transfer during deep fat frying of breaded chicken parts could lead to improved quality, time, and consumer value. They developed the heating model to predict the internal temperature profile within a chicken piece and used dimensional analysis to model the moisture loss problem for a given time-temperature history. These could eliminate time and tedious work for a new setting point for the fryer controller both to cook the chicken piece to doneness and achieve the desired breading attributes.

Farkas et al. (1996a and 1996b) presented the development of the mathematical equations used for modeling deep fat frying of an infinite slab. They described deep fat frying as a moving boundary problem and divided the slab sample into two regions, the crust and the core. The governing partial differential equations for heat and mass transfer was developed in each region. The results showed good agreement between predicted and experimental data.

Ni and Datta (1999) developed a multiphase porous media model to predict temperature, moisture, oil uptake, energy transport, and crust thickness of slab potato during deep fat frying process. To formulate the mathematical equations, the model considered the transport of oil, water, vapor, and air components separately. The results showed good agreement between the predicted and the experimental data for temperature and moisture profiles.

2.4 Factors Affecting the Oil Uptake

In the deep fat frying process, fats and oils play an important role by not only acting as a heating medium, but also offering special properties, including flavor and mouthfeel, that enhance the palatability of fried products. One of the most important quality parameters of fried products is the amount of fat absorbed during the frying process. Oil uptake has been identified as a crucial factor contributing to several health risks. The trend to consume more nutritious and healthier foods has forced the industry to reduce oil uptake in fried food products.

Understanding the factors contributing to oil uptake in fried foods using deep fat frying is crucial and may lead to improvement in producing lower fat content foods. A number of factors affecting oil uptake have been reported (Saguy and Pinthus, 1995).

2.4.1 Oil Quality and Composition

The selection of frying oil used in frying process is based on price, quality, flavor, oxidation susceptibility, functionality, and availability. The influence of oil composition on oil uptake, type of by products, and residues absorbed by deep-fat fried foods is widely documented (Blumenthal, 1991). Oil absorption and degradation of the oil increase with frying time; however, this relationship is not linear. It is found that the oil extracted from the fried food contains higher amount of polymers than the oil remaining in the fryer.

Blumenthal (1991) has developed a “frying fat quality curve” of potato crisp, which describes five phases that oil passes through during the degradation process.

1. Break-in oil. When frying begins with fresh oil in a clean fryer, the “break-in” stage, the food products are light in color; raw, ungelatinized starch at the center of the food; no cooked odor; no crisping of the surface; and little oil absorption. During this stage oil has little or no surfactant, so heat is not being transferred efficiently to the food.
2. Fresh oil. The food products are slight browning at the edges of the fries; partially cooked (gelatinized) centers; crisping of the surface; slightly more oil absorption. As food is continuously fried in oil, the degree of surfactant increases, resulting in improved food quality.
3. Optimum Oil. The food products produced in an “optimal” stages will have golden brown color; crisp; rigid surfaces; fully cooked at centers; delicious potato and oil odor; optimum level of oil absorption.
4. Degrading oil. As the oil continuously degrades, more surfactants are formed, causing increased contact between the food and oil. This results in darkened and/or spotty surfaces; excess oil pickup; product moving toward limpness; case-hardened surfaces.

5. Runaway oil. The food products are dark, case-hardened surfaces; excessively oily products; surface collapsing inward; centers not fully cooked and off-odor and off-flavor.

During frying, the breakdown of oil alters the oil quality and composition and forms a variety of small molecular substances affecting the oil quality. Among the compounds produced during oil degradation are surface-active components or surfactants, (Stern and Roth, 1959). Surfactants are soluble in both oil and water. They contain both hydrophilic and hydrophobic groups. There are two kinds of surfactants, water-activated and lipid-activated surfactants. Water-activated surfactants are soaps, phospholipids, and inorganic salts. Lipid-activated surfactants are low polar thermal polymers, which are carbon-carbon linked and high polar oxidative polymers. Blumenthal (1987) developed a surfactant theory which emphasized that controlling formation of surfactants is key to maintain the quality of oil and fried products (reduced oil uptake, better control of color) because surfactants acts as catalysts that enhance many of the breakdown reactions.

Blumenthal (1991) studied the characteristics of potato crisps fried in the different stages of oil and explained the frying phenomenon associating to surfactant theory. In a break in oil, there is a very high interfacial tension, and small bubbles form and then break rapidly on the surface of the oil due to low concentration of polymer formed and lower strength of the oil film of the steam dome. In fresh oil stage, small steam bubbles can persist longer. During optimum oil, with a moderate interfacial tension, medium size bubbles result. In degraded oil stage, with low interfacial tension, large persistent bubbles can be observed. In runaway oil, both large and small bubbles are presented and very persistent due to very low interfacial tension. The presence of large amount of polymer in degraded oil provides the elastic, sheet-forming, strong component of steam dome or bubbles.

Surfactants formed in the heated oil have a pronounced effect on oil absorption. These surfactants directly affect heat transfer at the oil-food interface by improving wetting capabilities of the oil and reducing the interfacial tension between the two immiscible materials because these compounds increase the contact between food and oil and cause excessive absorption of the oil by the food. This also results in an increase in

the heat transfer to the surface of the food (Stier and Blumenthal, 1990). Frying quality depends on surfactants that form when oil interacts with the food being fried (Stier and Blumenthal, 1990).

As the increase in heat transfer primarily affects the surface, the surface becomes darker and drier at a faster rate than the interior. This results in lower surfactant concentration to produce lower oil absorption by the food and less cooked exterior or interior of the food. Moderate concentration of surfactant produces normal absorption of oil and acceptable cooking of the exterior and interior. However, excessively high concentration of surfactant produces oil-soaked food with over cooked exterior and under cooked interior (Blumenthal, 1991).

2.4.2 Frying Temperature, Cooking Time and Product Surface Area

The temperature and cooking time affect the amount of heat transferred to the product and both are closely related (Gamble et al., 1987). Increased frying temperature generally decreases oil uptake as a result of the reduction in the overall time in the fryer. However, Pravisani and Calvelo (1986) had reported that increasing the frying temperature did not reduce the frying duration in the temperature range of 155°C to 200°C. Gamble et al. (1987) also found the amount of oil absorbed by a food product is independent of frying temperature. The reduction in oil uptake could be due to 1) the enhanced crust formation, which acts as an oil absorption barrier, 2) a decrease in the amount of water evaporated, and 3) a decrease in porosity. Thus, with higher temperatures and shorter cooking times, the oil uptake could be less. It is known that the larger the food surface is, the higher fat uptake is. A linear relation between the surface area and the amount of fat uptake has been reported by Gamble and Rice (1988).

Mallikarjunan et al. (1995) studied reduced frying time with increased oil temperature during frying of chicken nuggets. They reported that an increase in frying oil temperature resulted in an increase in oil uptake.

2.4.3 Moisture Content

Normally, the oil absorption takes place as a result of the removal of moisture from the food products. Most studies have reported that the higher initial moisture content resulted in an increased fat uptake. Lower initial moisture content presumably would lessen the internal volume of the food that could be occupied by oil during frying and would also shorten the frying time. Duxbury (1989) reported that food additives such as alginates and cellulose could play an important role in changing the amount of oil uptake and moisture loss. Moisture exits the food products mainly through diffusion. The effective water diffusion through the crust is, therefore, an important parameter that affects water evaporation and probably oil uptake. Pinthus et al. (1992, 1993) developed the term of U_R (oil uptake criterion) to express the weight ratio between oil uptake and moisture loss. This criterion was found to be instrumental in assessing the effectiveness of reducing oil uptake during deep fat frying.

2.4.4 Interfacial Tension

Interfacial tension, measuring the extent to which oil and water are able to mix together, is one of the important factors affecting the oil uptake during deep fat frying. Pinthus and Saguy (1994) reported that initial interfacial tension must be overcome during frying so that the oil can enter and absorb into the pores and holes. As interfacial tension is reduced to zero after absorption, it has been suggested that oil absorption takes place at the moving oil front interface. Oil absorption occurs initially at the surface of the food and then moves deeper into the food towards the core. They proposed that higher initial interfacial tension results in lower oil uptake. As the oil degrades, more surfactants are formed causing increased contact between the food and oil. This change results in excessive oil pickup by the food and an increased rate of heat transfer to the surface of the food.

An understanding of this phenomenon permits the explanation of results from several studies involving the interfacial tension during frying. Blumenthal and Stier (1991) developed the surfactant theory during frying. Increased surfactant content during

frying reduces the interfacial tension of the oil and causes increased contact and absorption of oil by the foods. Pinthus and Saguy (1994) used surface active agents on restructured potato products in studying the effect of the interfacial tension on oil uptake during deep fat frying. Using fundamental theories of surface chemistry, they were able to calculate the interfacial tension between the oil and food. Two parameters need to be measured which are the equilibrium contact angle (measured using a goniometer) and the surface tension of the frying liquid (measured with a tensiometer). The results showed lower oil absorption occurs when a higher interfacial tension existed. Interfacial tension was also found to affect the oil uptake throughout the frying process. As the interfacial tension will be reduced to zero after oil absorption on the surface, it was suggested that the oil absorption took place at a moving oil front surface.

2.4.5 Gel Strength

Gel strength is a general term involving several basic product characteristics, such as a cross-linking, compressibility, porosity, and others. Therefore, gel strength is important in restructured food products (snacks or potato products). Pinthus et al. (1992) used restructured potato product to assess the effect of gel strength on oil uptake. They showed that moisture loss and oil uptake was affected by gel strength. Pinthus et al. (1992) reported that higher gel strengths in restructured potato products markedly reduced the amount of oil absorption. Simultaneously, increasing the gel strength also reduced the moisture loss during deep fat frying. However, it was not possible to explain the effect of increased gel strength based only on the creation of a barrier resulting in the reduction of water movement to the surface, rate of evaporation and oil uptake. They suggested that other product characteristics such as porosity, internal structure, and compressibility could possibly be used to offer a better explanation of the oil uptake mechanism.

2.4.6 Porosity

Porosity is a significant factor affecting oil uptake in deep fat frying. The influence of porosity is manifested in two aspects: (1) the initial porosity of the product determines the final oil uptake in a linear relationship, and (2) both porosity and oil uptake increase during frying and also dependent on each other (Saguy and Pinthus, 1995).

Pinthus et al. (1995) reported a linear relationship existed between both porosity and bulk density. Porosity was also found to increase with frying time. The porosity of potato chips is caused by the rapid expansion of water vapor resulting from the high temperature of the frying medium. When a large volume of water vapor becomes trapped in the intracellular space, large pores may be created, and these pore spaces subsequently filled with oil. The more porous the food, the more space there is for oil to accumulate.

2.4.7 Product Shape and Structure

In potato crisp system, the migration of oil is limited to product surface, and no oil migration is found in other portions. Keller et al. (1986) were able to observe the oil migration in deep fried potato crisps by frying it in oil supplemented with 1-3 % Sudan Red B oil soluble dye. The same migration pattern is also reported by Gamble et al (1987) by using oil Red O for the same purpose. Contrary to potato crisps, in thinner potato chips, the oil migration took place throughout the product (Gamble, 1987). These observations support the relation between moisture loss and oil uptake. Thinner products allow moisture from almost all parts to evaporate producing a heterogeneous distribution of oil droplets. Further observations using chips with holes in the core and slicing using serrated blade to produce grooved regions also relate oil uptake to moisture loss during frying. In all these products oil is located in areas where moisture is most easily lost.

Gamble and Rice (1987) experimented using microwave, air-drying and freeze drying as pre-frying treatments to reduce oil uptake. They found that in freeze dried samples, oil uptake was higher with small droplets of oil in all regions of the slice. There are little or no oil free areas with the slices being totally covered with oil when compared

with microwave and air-dried samples. It was suggested that due to lower moisture level in freeze-dried sample, starch gelatinization did not occur. This in turn produces more free volume in the microstructure of the slices for oil absorption.

2.4.8 Crust

Many researchers have reported that oil uptake of food products during deep fat frying is localized in the crust (Keller et al., 1986; Gamble et al., 1987; Pinthus et al., 1995). In a study of oil infusion during frying, Keller et al. (1986) used an oil soluble dye to study oil infusion in fried potatoes. They found that the oil layer penetrated approximately 1 mm deep. However, Pinthus et al. (1995) reported that only approximately 35-38 % and 60-65 % of oil uptake was localized at the crust after 1 and 5 min, respectively. The depth of oil penetration is influenced by frying time, oil type, and oil quality (Stier and Blementhal, 1990).

The relationship between crust physical properties (thickness, gel strength, and porosity) and oil uptake has been studied by Pinthus et al. (1995). The crust layer serves as a mass transfer resistance. Thus, after a crust of approximately one millimeter develops, the frying process becomes a mass transfer limiting process. Restructured potato products of various gel strengths (defined by their deformability modulus) were fried for 1 and 5 min. After the early stage of frying, 1 min, crust thickness was not affected by product gel strengths (deformability modulus). However, thicker crusts were obtained for lower gel-strengths in the stages of frying, 5 min. Higher gel strength produces thinner crust and lower oil uptake.

Crust porosity decreases with frying time due to absorption of oil when moisture evaporates. This indicates that moisture loss provides only a partial explanation of oil uptake during frying. Other factors such as porosity, tortuosity and permeability may also be important factors in the oil uptake phenomenon.

Crust yield strength increases with an increase in frying time. Oil uptake increases at a fast rate with increasing crust yield strength up to a certain critical value. When the crust yield strength reaches approximately 210-240 kPa, no additional oil uptake is observed. This also occurs at different gel strength (Pinthus et al., 1995).

Almost all of these studies focused on the changes in products that initially contain no or little amount of fat. Due to the importance of crust in limiting heat and mass transfer, its effects on oil uptake during deep fat frying of fatty foods may prove to be very beneficial in further understanding the oil transfer process.

2.5 Changes in Frying Oils during Deep Fat Frying

A number of changes take place in frying oils during heating and deep fat frying, involving a complex pattern of thermolytic and oxidative reactions. To obtain the maximum quality of fried products, a good understanding in physical and chemical changes of fats and oils is necessary to further determine the relationship of these compounds to nutritive value, toxic effects of the heated oil, and sensory quality of the oil and food fried in it.

2.5.1 Physical Changes in Oils during Deep Fat Frying

The physical changes occurring in the oil during frying include darker color, increased viscosity, decreased smoke point, and increased foaming. In fresh frying oil, temperature must be over 204°C before enough volatile material present to visually appear as smoke. As the oxidation and hydrolysis continue, the breakdown products begin to concentrate, and smoke appears at lower and lower temperatures (Moreira, 1999). When the frying oil is heated and used for a period of time, the oil color darkens due to oxidative reactions. The mechanism for the formation of highly colored compounds is still not fully understood. Melton (1994) proposed that the color changes in fried food can also dissolve in the oil and will tend to darken the frying oil. The abused oil may thicken and becomes more viscous due to polymerization, oxidation, hydrolysis, and isomerization. Thickening reduces the rate of heat transfer so it takes longer to cook and causes more oil absorption (Moreira, 1999). Chang et al. (1978) reported that foods fried in the oil with a foaming tendency are often greasy and less crispy.

2.5.2 Chemical Changes in Oils during Deep Fat Frying

During deep fat frying, the oil is exposed continuously or repeatedly to elevated temperatures in the presence of air and moisture. A number of chemical reactions occur involving complex thermolytic and oxidative reactions. The reactions consist of hydrolysis, oxidation, and polymerization. As these reactions proceed, the functional, sensory, and nutritional qualities of the oil change and may eventually reach a point where it is no longer able to be used for preparing high quality fried products and it must be discarded.

Hydrolysis

The major chemical reaction taking place during commercial deep fat frying is hydrolysis due to large amounts of water introduced from food and the relatively high temperatures at which the oil is maintained. Hydrolysis is the reaction of the water, in the form of steam, released from the food to react with triglyceride and form free fatty acids (FFA), monoglyceride, diglyceride, and glycerol. Newar (1985) reported that excess fatty acids produced in the course of frying are associated with decreases in the smoke point and surface tension of the oil and poor quality of fried food. In addition, FFAs continue to breakdown to small molecules that develop off flavors in the fried food.

Pyrolysis

Pyrolysis is the formation of lower molecular weight compounds, due to the extensive breakdown of the chemical structure of oil in the frying process (Moreira, 1999). One of the compounds forming when oils are overheated or pyrolyzed is acrolein, a pungent irritant, which can make the working environment quite uncomfortable. Acrolein is formed from glycerol left from hydrolysis of triglycerides.

Oxidation

Oxidation is the only reaction that takes place during storage. Oxidation is the reaction of atmospheric oxygen with the oil at its surface. This oxygen attacks the double bonds of the oil structure producing hydroperoxides, the primary oxidative product.

Since hydroperoxides are very unstable and flavorless, they further undergo three major types of degradation: (1) fission forms alcohols, aldehydes, acids, and hydrocarbons, thereby also contributing to the darkening of the frying fat and flavor changes; (2) dehydration forms ketones; or (3) formation of free radicals which form a variety of chemical products such as oxidized monomers, oxidized dimers, trimers, epoxides, alcohols, and hydrocarbons, which contribute to the increases in viscosity.

During the standby and frying period, the oil is still heated in the presence of air, and the process of oxidation becomes rapid. As a result of the breakdown of the double bonds in the oil structure, new compounds are formed in the fryer and have distinctly unpleasant odors. These compounds represent the off tastes and off flavors in the fried products (Moreira, 1999). In addition, some metals such as iron and copper, can accelerate the oxidation of frying oils.

Polymerization

Thermal alteration results in the formation of cyclic monomers, dimers and cyclic compounds through polymerization occurring due to the exposure to high temperature for an extended period of time. The molecules rearrange and the double bonds often end up closer together. Isomerization can make the oil more sensitive to oxidation. Accumulation of these compounds increases viscosity, foaming, and color darkening.

Moreira et al. (1999) reported that more than 400 different chemical compounds, including 220 volatile compounds, were identified in the deteriorated oil. Degradation products other than nonpolar fractions are collectively called polar fraction. The polar fraction is subsequently divided into two groups including polymers and decomposition products. The term of polymer refers to the group of all the degradation products with higher molecular weight than triglyceride. On the other hand, the term of decomposition products represents all the group of compounds with lower molecular weight than triglyceride. In general, the major decomposition products formed during frying are volatile decomposition products (VDP) with molecular weights less than 1800 daltons and nonvolatile decomposition products (NVDP) with molecule weights greater than 1800 daltons.

Volatile Decomposition Products

Most of the VDPs are being formed by continuous oxidation, hydrolysis, and thermal or pyrolytic reactions as well as being removed by the volatilization during frying. Characterization of volatile decomposition products (VDPs) is important because it may help in understanding the chemical reactions taking place during frying (White, 1991). In addition, the VDPs are responsible for deep fried flavor. A great number of VDPs distill out during frying, so care must be taken to capture these compounds for an accurate measure of heat abuse. The measurement of VDPs is very time consuming and tedious. Other methods for measuring heat abuse in frying oils have been more popular. Few studies have been done so far on the measurement of VDPs because of the complexity of the work and difficulty in quantifying the VDPs. Chang et al. (1978) suggested that characterization of the VDPs is important for three reasons:

1. The mechanisms for the formation of these products may help to differentiate those which lead to the formation of nonvolatile products since both types are produced simultaneously
2. The VDPs are inhaled by the deep frying operators and a portion of the VDPs is retained in the fried food and thus enters the consumer's diet; the effects of these compounds on human health should be investigated.
3. The flavor of deep fat fried food is partly due to the VDPs, and a knowledge of their chemical composition could make it possible to develop synthetic flavors which could be used to enhance the flavor of food products without frying.

Chang et al. (1978) attempted to measure the VDPs from corn oil, hydrogenated cottonseed oil, trilinolein, and triolein under an elaborate system involving simulated deep fat frying conditions. The VDPs from the oil samples were collected, separated into two parts including acidic and nonacidic compounds, and then fractionated by repeated gas chromatography with polar and nonpolar columns. The pure gas chromatographic fractions were then identified by a combination of retention time and infrared and mass spectrometry. A total of 220 VDPs were identified. Many of the compounds are known to be toxic, others are known as flavor contributors to fried food.

Nonvolatile Decomposition Products

Whereas the VDPs escape from the frying oil, the nonvolatile decomposition products (NVDPs) still remain in the frying fat to promote further degradation of oil. The NVDPs are subsequently absorbed by the fried food, and hence are eaten by the consumers. The formation of NVDPs is due to thermal oxidation and polymerization of the unsaturated fatty acids present in the frying medium. The formation and accumulation of the NVDPs are responsible for physical changes in the frying fat such as increases in viscosity, color, and foaming, as well as chemical changes such as increases in fatty acids, carbonyl value, hydroxyl content, saponification value, and decreases in unsaturation, with resulting increases in the formation of high molecular weight products.

Measurement of NVDPs provides better methods to describe degradation of a frying oil because they are nonvolatile and their accumulation is steady. Paradis and Newar (1981) also confirmed that the higher molecular weight compounds are reliable indicators of oil quality.

2.6 Measurement of Frying Oil Quality

The measurements of degradation in frying oils and factors that affect fried food flavor have been reviewed by Melton et al. (1994). It is difficult to obtain a single test measuring all conditions at once and applicable to all fats, all foods, or all conditions of processing. However, the method most often used by different countries to determine when to discard a frying oil still is sensory evaluation.

As a result of substantial changes in physical and chemical properties of oils, the measurement of thermally oxidative alteration has been carried out almost exclusively by means of physical and chemical indices, which is still a common and useful practice. Physical tests include viscosity, color, foaming, ultraviolet absorption, dielectric constant, and organoleptic assessment. Chemical tests include acid value, iodine value, peroxide value, FFA, TPM, anisidine value, and colorimetric reactions.

Melton et al. (1994) summarized methods for measuring frying oil degradation based on physical characteristics of oil, volatile decomposition products (VDPs), and nonvolatile decomposition products (NVDPs). Most of these methods are laboratory

techniques for measurement rather than quick test kits. Quick test kits are also available providing a rapid test to measure deterioration of frying oil by means of either VDPs or NVDPs. The quick tests are based on one chemical change occurring in the oil and are not always accurate. However, a speedy test for estimation of oil quality is necessary to rapidly monitor oil quality undergoing in frying process and inspect the oil quality in fast food restaurants (White, 1991).

Currently, no test has been recognized as the best indicator of the frying oil quality. The snack food industry tends to use FFA content as a chemical marker for predicting oil stability on the products as they pass through distribution to the consumer. However, the measurement of the total polar materials (TPMs) in frying oil has been proposed as a possible method, and many researchers believe it is one of the best indicators of the frying oil quality.

Perkin (1967) reported that the formation and accumulation of NVDPs are responsible for physical changes in the frying oil, such as increases in viscosity, color, and foaming, and for chemical changes, such as increases in free fatty acids (FFAs), carbonyl value, hydroxyl content, and saponification value, decreases in unsaturation, and ultimately increases the formation of high molecular weight products. Most methods for determining the deterioration of frying oil depended on these changes.

Traditional methods to determine NVDPs include free fatty acid (Johnson and Kummerow, 1957; Fritsch, 1981; Stevenson et al., 1984), iodine value (Waltking and Zmachinski, 1970; Sims, 1955), nonurea-adduct forming ester (Alim and Morton, 1974; Firestone et al., 1970), and viscosity (Alim and Morton, 1974; Stevenson et al., 1984).

The U.S. Department of Agriculture's (USDA) guidelines for controlling the equality of processed foods such as battered and breaded chicken, fish, or meat require that the frying oil must contain less than 2 % FFA (Moriera et al., 1999). Free fatty acids are the primary initial breakdown products resulting from triglyceride degradation. The percentage of FFA is not linearly related to the degradation of the oil, so it should not be the only one index of the oil quality during process. As the result of heat, light, and oxidation, the FFAs are converted into a variety of other polar molecules (Moriera et al., 1999). Like FFA, hydroperoxides, the primary oxidation product, are very unstable and decompose via fission, dehydration, and the formation of free radicals. Thus, the

peroxide value is not a good measurement of heat abuse in frying oils (White, 1991). Several other methods have developed as a useful tool in determination of abused frying oils by measuring the specific group of compounds formed during frying process.

2.6.1 Standard Methods

White (1991) summarized several methods that have been widely used and subsequently adopted as standard procedures. These methods include the measurements of polar component, conjugated dienoic acids, and fatty acid 18:2/16:0 ratio.

Polar Components

White (1991) reported that the determination of total polar materials (TPMs) has proven to be accurate, simple, and reproducible methods for evaluating frying oil quality. Currently, it is approved as a standard method of IUPAC (1987) and AOAC (1984). To determine total polar materials, a weighed amount of fat (2.5 g) is dissolved in light petroleum ether: diethyl ether (87:13) and then run through a silica gel column that absorbed the polar compounds. After evaporation of the eluted solvent, the nonpolar fat is weighed and the total polar materials estimated by the difference. The polar materials remaining on the column can be eluted with diethyl ether. However, this method is time consuming approximately as 3.5 hr is needed to run one sample).

Paradis and Newar (1981) stated that when a concentration of 25-27 % of total polar materials has accumulated, the frying oil should be discarded. Although the measurement of TPM is a popular method for following the oil degradation, more research is needed to determined the TPM levels at which different frying oils should be discarded, and to relate TPM levels to fried food quality for different types of frying oil (White, 1991).

Conjugated Dienoic Acids

During the oxidation of polyunsaturated fatty acids, a shift in one of the double bonds takes place, and then a conjugated diene is formed. These substances in frying oil can be measured by ultraviolet absorption at 2332 nm. Currently, the official methods for this procedure are available in IUPAC and AOAC. The absorbance increases initially,

and then plateaus during frying. This test is more useful in measuring heat abuse of polyunsaturated oils, but it is less applicable to fat containing few unsaturated bonds (Peled et al., 1975).

Fatty acid analyses and 18:2/16:0 Ratio

Many researchers have monitored fatty acid changes in oil and fat during frying process, using standard methods such as AOCS method Ce-1-62. Based on the reported literature, the changes in the ratio of fatty acid C18:2 to C16:0 has been correlated satisfactorily to other chemical measurements (Melton et al., 1994).

2.6.2 Quick Test

Several commercially available procedures have been developed to provide a rapid means of testing oil quality. These tests are based on chemical changes formed in the oil and are not always accurate. However, the development of a reliable rapid test is still needed. The quick tests often used in fried food industry include FoodOil sensor, RAU-test, Fritest, Spot test, and ACM quick test.

Dielectric Constant

A quick method that measures the dielectric constant has been used to estimate frying oil degradation (Fritsch et al., 1979; Graziano, 1979). As the frying degrades, there is an increase in the number of polar compounds, which directly increases the dielectric constant. The procedure is useful in some settings, but it would be difficult to adapt it to production situations because the reading is influenced by a lot of outside factors such as water or fat extracted from the fried food. Graziano (1979) also reported that fresh oils differ in dielectric constant, so the instrument must be standardized each time an oil is tested. Generally, the more saturated fatty acids have a lower value than the highly unsaturated fat. Northern States Instrument Corp. (Lino Lakes, MN) provides a portable electronic instrument, the Foodoil Sensor (FOS) that measures the dielectric constant in the frying oil (Fritsch, 1981). It is suggested that an FOS reading of 4.0 should be the upper limit and oil should be discarded if the FOS reading is above 4.

RAU-Test

This test is marketed by E. Merck, Darmstadt, Germany, under the name of Oxifrit-Test (Croon et al., 1986). It is a colorimeter test kit that contains redox indicators that react with the total amount of oxidized compounds in the fat sample. The developed color of the mixture of the sample and reagents is compared to a four-color scale, with 1 representing good, 2 still good, 3 intermediate quality, and 4 bad. One problem with this method is that it requires the mixing of flammable organic solvents which could be hazardous if done near the fryer.

Fritest

This test is a colorimeter test that is sensitive to carbonyl compounds. The mixture of sample and reagent is compared to three diagnostic colors, with 1 representing good, 2 intermediate, and 3 bad.

Spot Test

This test is also a colorimeter test described by Robern and Gray (1981). To test the oil, a drop is placed on a silica gel covered slide that has bromocresol green incorporated into the gel as a pH indicator of hydrolytic rancidity. The diagnostic colors of the pH-indicator are blue, green, and yellow.

Quick Test for Alkaline Contaminant Materials

This colorimeter test shows the presence of semiquantitative concentration of alkaline contaminant materials (ACMs) such as soaps, that accumulate in used frying fats from the interaction of food materials with oil degradation products. The procedure measures “soaps” at the level from 0 to 200 ppm. A test kit solution containing bromophenol blue as a pH indicator, sodium hydroxide, and hydrochloric acid are added to the oil, and the oil and solution are shaken in a test tube. The oil quickly forms a lower layer, and the transparent upper layer assumes a color directly proportional to the amounts of soaps or ACMs extracted from the oil.

2.6.3 Complex Procedures

Several methods have been developed to study the deterioration of the frying oils and fats such as gas-liquid chromatography (GLC), liquid chromatography (LC), and size-exclusion chromatography (SEC).

Waltking and Zmachinski (1970) used GLC to quantify the total polymers in heat-abused oil by using a complex formula relating the peak area of an internal standard to the amount of noneluted materials. Guillaumin and Gente (1977) used GLC to analyze cyclic monomers in heated fats. Paradis and Nawar (1981) developed a GLC procedure to determine the amount of dimeric triglycerides in the abused oil. This compound is used as a marker to represent the state of deterioration of the abused oil in frying process.

2.7 Edible Films in Frying Process

Currently, there exists an interest in reducing the oil uptake in fried food products by using edible films and coatings. Edible films and coatings are natural polymers obtained from agricultural materials. They are traditionally used to improve food appearance and conservation (Cuq et al., 1995; Debeaufort et al., 1998). Suitably selected edible films and coatings can improve the consumer acceptability of fried products by reducing fat absorption as well as maintain the quality of frying oil over a longer period of time by controlling the migration of certain components between the product and the frying oil.

Polysaccharides such as vegetable and microbial gums, starches, cellulose and derivative have good film forming properties (Duxbury, 1989). Films formed from these hydrophilic compounds provide efficient barriers against oils and lipids, but their moisture barrier properties are poor (Cuq et al., 1995; Nisperos-Carriedo, 1994). Although coating by polysaccharide polymers may not provide a good water vapor barrier, these coatings can act as a sacrificing agent and retard moisture loss from the food (Kester and Fennema, 1986). An edible film usually is an integral part of the food product it encloses and therefore must have neutral sensorial properties (or compatible with product nature) so as not to be detected during consumption (Cuq et al., 1995; Debeaufort et al., 1998).

Edible coatings prepared from ingredients such as polysaccharides, protein, lipids or their combinations have been used as a part of batters and breading to improve battering and coating performance (Kester and Fennema, 1986; Debeaufort et al., 1998; Dziezark, 1991; Sanderson, 1981). By suitable selection of edible films it is possible to control moisture and fat transfer between the frying medium and the food (Mallikarjunan et al., 1997). Methylcellulose (MC) and hydroxymethylcellulose (HPMC) film possess good film forming characteristics; films are generally odorless and tasteless, flexible and are of moderate strength, transparent, resistance to oils and fats, water-soluble, and have moderate resistance to moisture and oxygen transfer (Krochta and Mulder-Johnston, 1997; Nisperos-Carriedo, 1994). MC and HPMC can form a thermally induced gelatinous coating; thus they have been used to retard oil absorption in deep frying food products (Baker et al., 1994; Balasubramaniam et al., 1997; Dziezark, 1994; Kester and Fennema, 1986; Mallikarjunan et al., 1997; Nisperos-Carriedo, 1994; Sanderson, 1981).

Balasubramaniam et al. (1995 and 1997) demonstrated that there is the potential of edible films for moisture retention and reduction in fat absorption during frying of poultry products. Compared to uncoated samples, the coating of edible films on chicken balls (nuggets) reduced the fat absorption in the surface layer up to 17.9 % and the core up to 33.7 % reduction. Mallikarjunan et al. (1997) studied the moisture retention and fat reduction capabilities of different edible film coatings during deep fat frying of starchy products. Results showed moisture retention from 22 % to 31 % for MC and HPMC, respectively and also reduction in oil uptake of 83.6 % and 61.4 % for MC and HPMC, respectively.

Summary

Deep fat frying is a complex cooking method involving heat, moisture, and fat transfer leading to physical and chemical changes in fried product and frying medium. This chapter extensively reviewed the frying mechanisms, factors affecting oil quality and implications of oil quality to product quality. This chapter also includes information related to measurements of oil quality.

REFERENCES

- Alim, H. and Morton, I.D. 1974. Oxidation in foodstuffs fried in edible oils. Proc. of IV Intl. Cong. On Food Sci. and Technol., Vol. I, p. 345.
- AOAC. 1984. Polar components of frying fats, Method 18.074. In "Official Methods of Analysis," 14th ed. Assn. of Official Analytical Chemists, Washington, D.C.
- Ashkenazi, N., Mizrahi, S. and Berk, Z. 1984. Heat and mass transfer during frying. In "Engineering and Food", Vol.1, ed., p. 109-116. B.M. McKenna. Elsevier Applied Science Publishers, New York.
- Ateba, P. and Mittal, G.S. 1994. Modeling the deep-fat frying of beef meatballs. Intl. J. Food Sci. Technol. 29: 429-440.
- Baker, R.A., Baldwin, E.A. and Nisperos-Carriedo, M.O. 1994. Edible coatings and films for processed foods. Ch. 4 in "*Edible Coatings and Films to Improve Food Quality*," p. 89-104. J.M. Krochta, E. Baldwin and M.O. Nisperos-Carriedo (Ed.). Technomic Publishing Comp. Inc., Lancaster, PA.
- Balasubramaniam, V.M., Chinnan, M.S. and Mallikarjunan, P. 1995. Deep-fat frying of edible film coated products: experimentation and modeling. Food Processing Automation IV, Proceedings of the FPAC IV Conference, Chicago, IL, November 3-5, St. Joseph, MI: American Society of Agricultural Engineers, p. 486-493.
- Balasubramaniam, V.M., Chinnan, M.S., Mallikarjunan, P. and Philips, R.D. 1997. The effect of edible film on oil uptake and moisture retention of a deep-fat fried poultry product. J. Food Proc. Eng. 20: 17-29.
- Blumenthal, M.M. 1987. "Optimum Frying: Theory and Practice," 2nd ed. Libra Laboratories, Inc., Piscataway, NJ.
- Blumenthal, M.M. 1991. A new look at the chemistry and physics of deep-fat frying. Food Technol. 45(2): 68-71, 94.
- Chang, S.S., Peterson, R.J. and Ho, C.T. 1978. Chemical reactions involved in deep fry frying of foods. J. Am. Oil Chem. Soc. 55: 718-722.
- Croon, L.B., Rogstad, A., Leth, T. and Kiutomo, T. 1986. A comparative study of analytical methods for quality evaluation of frying fat. Fette Seifen Anstrich. 88: 87-92.

- Cuq, B., Gontard, N. and Guilbert, S. 1995. Edible films and coating as active layers. Ch. 5 In “*Active Food Packaging*”, M.L. Rooney (Ed.), p. 111-142. Blackie Academic & Professional, Glasgow.
- Debeaufort, F., Quezada-Gallo, J.A. and Voilley, A. 1998. Edible films and coatings: Tomorrow’s packagings, A review Crit. Rev. Food Sci. 38(4): 299-313.
- Duxbury, D.D. 1989. Oil/water barrier properties enhanced in fried food, batters. Food Proc. 50(2): 66-67.
- Dziezak, J.D. 1991. A focus on gums. Food Technol. 45(3): 116-132.
- Farkas, B.E. 1994. Modeling immersion frying as a moving boundary problem. Ph.D. dissertation. Univ. of California, Davis.
- Farkas, B.E., Singh, R.P. and Rumsey, T.R. 1996a. Modeling heat and mass transfer in immersion frying. I, Model development. J. Food Eng. 29: 211-226.
- Farkas, B.E., Singh, R.P. and Rumsey, T.R. 1996b. Modeling heat and mass transfer in immersion frying. I, Model solution and verification. J. Food Eng. 29: 227-248.
- Firestone, D. 1970. The determination of polymers in fats and oils. J. Am. Oil Chem. Soc. 40: 247-249.
- Fritsch, C.W. 1981. Measurements of frying fat deterioration: A brief review. J. Am. Oil Chem. Soc. 58: 272-276.
- Fritsch, C.W., Egberg, D.C. and Magnuson, J.S. 1979. Changes in dielectric constant as a measure of frying oil deterioration. J. Am. Oil Chem. Soc. 56: 746-750.
- Gamble, M.H. and Rice, P. 1987. Effect of pre-drying of oil uptake and distribution in potato chip manufacture. J. Food Sci. Technol. 22: 535-540.
- Gamble, M.H. and Rice, P. 1988. The effect of slice thickness on potato crisp yield and composition. J. Food Eng. 8: 31-46.
- Gamble, M.H., Rice, P. and Selman, J.D. 1987. Relationships between oil uptake and moisture loss during frying of potato slices from c.v. Record U.K. Tubers. Intl. J. Food Sci. Technol. 22: 233-241.
- Graziano, V.J. 1979. Portable instrument rapidly measures quality of frying fat in food service operations. Food Technol. 33(9): 50-53.

- Guillaumin, R. 1988. Kinetics of fat penetration in food. In "*Frying of Food. Principals, Changes, New Approaches*", (Ed.), G. Varela, A.E. Bender, and J.D. Morton. Ellis Horwood, Chichester, England.
- Guillaumin, R. and Gente, M. 1977. Determination of cyclic monomers. *Rev. Fr. Corps. Gras.* 24: 211-214.
- IUPAC. 1987. Evidence of purity and determination from ultraviolet spectroscopy, Method 2.505, and Determination of polar compounds in frying fats, Method 2.507. In "Standard Methods for Analysis of Oils, Fats and Derivatives," 7th ed. IUPAC App. Chem. Commission on Oils, Fats and Derivatives, ed. C. Paquot and A. Hautfenne, Blackwell Scientific Publications, Oxford, England.
- Jacobson, G.A. 1991. Quality control in deep-fat frying operations. *Food Technol.* 45(2): 72-74.
- Johnson, O.C. and Kummerow, F.A. 1957. Chemical changes which take place in an edible oil during thermal oxidation. *J. Am. Oil chem. Soc.* 34: 407-411.
- Keller, C. and Escher, F. 1989. Heat and mass transfer during deep fat frying of potato products. Presented at Intl. Congress on Engineering and Food 5., Cologne, Germany, May 25-June 1.
- Keller, C., Escher, F. and Solm, J.A. 1986. A method for localizing fat distribution in deep-fat fried potato products. *Lebensm.-Wiss. U. Technol.* 19: 346-348.
- Kester, J.J. and Fennema, O.R. 1986. Edible films and coating: A review. *Food Technol.* 40(12): 47-59.
- Kozempel, M., Tomasula, P.M. and Craig, J.Jr. 1991. Correlation of moisture and oil concentration in french fries. *Lebensm.-Wiss. U. Technol.* 24: 445-448.
- Krochta, J.M. and Mulder-Johnson, K. 1997. Edible and biodegradable polymer films: challenges and opportunities. *Food Technol.* 51(2): 61-73.
- Kulp, K. and Loewe, R. 1996. Batters and breading in food processing. St. Paul, American Association of Cereal Chemist, Inc.
- Lin, S., Akoh, C.C. and Reynolds, A.E. 1998. The recovery of used frying oils with various adsorbents. *J. Food Lipids.* 5: 1-16.
- Levine, L. 1990a. Understanding frying operations, Part I. *Cereal Foods World.* 35: 272-273.

- Levine, L. 1990b. Understanding frying operations, Part II. *Cereal Foods World*. 35: 514-517.
- Mallikarjunan, P., Chinnan, M.S. and Balasubramaniam, V.M. 1995. Modeling deep-fat frying of chicken coated with edible films. Presented at Ann. Mtg., Inst. of Food Technologists, Anaheim, CA, June 3-7.
- Mallikarjunan, P., Chinnan, M.S., Balasubramaniam, V.M. and Philips, R.D. 1997. Edible coating for deep-fat frying of starchy products. *Lebensm-Wiss. U. Technol.* 30: 709-714.
- Melton, S.L., Jafar, S., Sykes, D. and Trigiano, M.K. 1994. Review of stability measurements for frying oils and fried food flavor. *J. Am. Oil Chem. Soc.* 71: 1301-1308.
- Mittelman, N., Mizrahi, S. and Berk, Z. 1984. Heat and mass transfer in frying, Ch. 12. In *"Engineering and Food"*. B.M. McKenna. Elsevier Applied Science Publishers, New York.
- Moriera, R.G., Castell-Perez, M.E. and Barrufet, M.A. 1999. Frying oil characteristic, In *"Deep-Fat Frying Fundamental and Applications,"* Ch.3, p. 33-74. 1st ed. Aspen Publication, Gaitherburg, MA.
- Moreira, R.G., Palau, J.E., Castell-Perez, M.E. and Sweat, V.E. 1991. Moisture loss and oil absorption during deep fat frying of tortilla chips. Presented at Winter Mtg., Am. Soc. Agri. Eng., St. Joseph, Mich.
- Moreira, R.G., Palau, J.E. and Sun, X. 1995. Simultaneous heat and mass transfer during the deep fat frying of tortilla chips. *J. of Food Process Eng.* 18: 307-320.
- Newar, W.W. 1985. Lipids. In *"Food Chemistry,"* ed. O.R. Fennema, p. 175-189. Marcel Dekker, New York, NY.
- Ni, H. and Datta, A.K. 1999. Moisture, oil and energy transport during deep-fat frying of food materials. *Trans IchemE.* 77: 194-204.
- Nisperos-Carriedo, M.O. 1994. Edible coatings and films based on polysaccharides. Ch. 11 in *"Edible Coatings and Films to Improve Food Quality,"* p. 305-335. (Ed.). J.M. Krochta, E.A. Baldwin and M.O. Nisperos-Carriedo., Technomic PublishingComp. Inc., Lancaster, PA.

- Orthoefer, F.T. 1988. Care of food service frying oils. *J. Am. Oil. Chem. Soc.* 65(9): 1417-1419.
- Orthoefer, F.T. and Cooper, D.S. 1996. Evaluation of used frying oil. Ch. 16 in “ Deep Frying. Chemistry, Nutrition, and Practice Applications,” E.G. Perkins and M.D. Erickson (Ed.), p. 285-296. AOCS Press, Champaign, IL.
- Paradis, A.J. and Nawar, W.W. 1981. Evaluation of new methods for the assessment of used frying oils. *J. Food Sci.* 46: 449-453.
- Paul, S. and Mittal, G.S. 1997. Regulating the use of degraded oil/fat in deep fat/oil food frying. *Critic. Rev. Food Sci. Nutri.* 37(7): 635-662.
- Peled, M., Gutfinger, T. and Letan, A. 1975. Effect of water and BHT on stability of cottonseed oil during frying. *J. Sci. Food Agric.* 26: 1655-1688.
- Perkin, E.G. 1967. Formation of non-volatile decomposition products in heated fats and oils. *Food Technol.* 21: 125.
- Perkin, E.G. 1992. Effect of lipid oxidation on oil and food quality in deep frying. Ch. 18 in “ Lipid oxidation in food,” p. 310-312. A.J. St. Angelo (Ed.). American Chemical Society, Washington, DC.
- Pinthus, E.J. and Saguy, I.S. 1994. Initial interfacial tension and oil uptake by deep-fat fried foods. *J. Food Sci.* 59(4): 804-807, 823.
- Pinthus, E.J., Weinberg, P. and Saguy, I.S. 1992. Gel-strength in restructured potato product affects oil uptake during deep-fat frying. *J. Food Sci.* 57: 1359-1360.
- Pinthus, E.J., Weinberg, P. and Saguy, I.S. 1993. Criterion for oil uptake during deep-fat frying. *J. Food Sci.* 58: 204-205, 222.
- Pinthus, E.J., Weinberg, P. and Saguy, I.S. 1995. Oil uptake in deep fat frying as affected by porosity. *J. Food Sci.* 60: 767-769.
- Pravisani, C.I. and Calvelo, A. 1986. Minimum cooking time for potato strip frying. *J. Food Sci.* 51: 614-618.
- Rhee, K.S. Housson, S.E. and Ziprin, Y.A. 1992. Enhancement of frying oil stability by a natural antioxidative ingredient in the coating system of fried meat nuggets. *J. Food Sci.* 57(3): 789-791.
- Rice, P. and Gamble, M.H. 1989. Technical note: Modeling moisture loss during potato slice frying. *Intl. J. Food Sci. Technol.* 24:183-187.

- Roa, V.N.M. and Delaney, A.M. 1995. An engineering perspective on deep-fat frying of breaded chicken pieces. *Food Technol.* 49(4): 138-141.
- Roborn, H. and Gray, L. 1981. A colorimetric spot test for heated oils. *Can. Inst. Food Sci. Technol. J.* 14: 150-153.
- Saguy, I.S. and Pinthus, E.J. 1995. Oil uptake during deep-fat frying: Factors and mechanism. *Food Technol.* 49(4): 142-145, 152.
- Sahin, S., Sastry, S.K. and Bayindirli, L. 1999. The determination of convective heat transfer coefficient during frying. *J. Food Eng.* 39: 307-311.
- Sanderson, G.R. 1981. Polysaccharides in Foods. *Food Technol.* 37(7): 50-57, 83.
- Sims, R.P.A. 1955. Possible mechanisms in thermal polymerization of vegetable oils. II. Polymer formation. *J. Am. Oil Chem. Soc.* 34: 466-469.
- Singh, R.P. 1995. Heat and mass transfer in foods during deep-fat frying. *Food Technol.* 49(4): 142-145,152.
- Stern, S. and Roth, H. 1959. Properties of doughnut frying fat. *Cereal Sci. Today.* 4(6): 176-179.
- Stevenson, S.G., Jeffery, J., Vaisey-Genser, M., Fyfe, B., Hougen, F.W. and Eskin, N.A.M. 1984. Performance of canola and soybean fats in extended frying. *Can. Inst. Food Sci. Technol. J.* 17: 187-190.
- Stier, R.F. and Blumenthal, M.M. 1990. Heat transfer in frying. *Baking and Snack System*, 12: 15-19.
- Tan, Y.A., Ong, S.H., Berger, K.G., Onn, H.H. and Poh, B.L. 1985. A study of the cause of rapid color development heated refined palm oil. *J. Am. Oil. Chem. Soc.* 62(6): 999-1006.
- Varela, G. 1988. Current facts about the frying food. In "Frying of Food: Principles, Changes, New Approaches," pp. 9-25, Chichester, Ellis Horwood.
- Waltking, A.E. and Zmachinski, H. 1970. Fatty acid methology for heated oils. *J. Am. Oil Chem. Soc.* 47: 530-134.
- White, P.J. 1991. Methods for measuring changes in deep-fat frying oils. *Food Technol.* 45(2): 75-80.

CHAPTER 3

The Effect of Pressure Conditions on Quality of Chicken Nuggets Fried with Constant Frying Time

ABSTRACT

The potential for using nitrogen gas as a pressurizing medium in a deep fat fryer was investigated. To achieve the desirable characteristics of fried chicken nuggets, the effects of different frying temperatures (150°C, 175°C, and 190°C) and pressures (163, and 184 kPa) on the fried food quality were studied. Chicken nuggets were fried for 240 s in a modified restaurant type pressure fryer. Modifications were made to include external gases to pressurize the frying chamber. The quality characteristics of the fried products were determined.

An increase in pressure applied during frying resulted in tender and juicier fried products due to the reduction in moisture loss. The increase in pressure reduced the oil uptake by the fried products. Compared with the use of steam released from the food, frying under nitrogen gas provided similar or better quality of fried products in terms of moisture retention, juiciness, and texture. An increase in frying oil temperature increased the moisture loss, and crust oil uptake. In addition, the fried products were harder and less juicy ($P<0.05$). An increase in frying temperature directly influenced crust color of fried foods. The crust became significantly darker ($P<0.05$).

Keywords: pressure frying, nitrogen gas, steam, chicken nuggets, moisture retention, oil uptake

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INTRODUCTION

Frying is still an important food preparation technique despite some health concerns due to high fat consumption. Frying oil consumption is measured in millions of pounds per year. The development of both industrial and foodservice frying equipment has led to an increase of fried foods in the American diet. Deep fat frying is a popular restaurant preparation method because it is fast and convenient. In the United States, fried food is a multi-billion dollar industry and most food service operations rely heavily upon deep fat frying for cooking french fries, poultry, meat, seafood, and vegetables.

The popularity of deep-fried products is due to the basic structure in which they are cooked (Stevenson et al., 1984). The unique property of a soft and moist interior along with the porous outer crispy crust of fried food provides increased palatability (Orthofer et al., 1996; Varela, 1988). The key attributes of deep fat frying are high temperature, rapid heat transfer, and absorption of some frying fat. The oil provides an effective medium for energy transfer from the heat source to the food (Orthofer et al., 1996). The oil absorption into the product during deep fat frying is influenced by: oil temperature (Guillaumin, 1988), frying time and surface moisture content (Lamberg et al., 1990), product surface area (Gamble and Rice, 1988), pressure (Roa and Delaney, 1995; Mallikarjunan et al., 1995), and frying oil quality (Tseng et al., 1994). Various researches have studied the effect of frying parameters, but they have been primarily limited to non-fatty fried products. A few researchers have been studied the relationship between oil uptake and moisture loss on breaded chicken products during pressure frying (Roa and Delaney, 1995; Mallikarjunan et al., 1995).

Pressure frying method is known to yield more juicy and tender products than atmospheric pressure (Roa and Delaney, 1995; Mallikarjunan et al., 1995). By appropriately selecting temperature and pressure in deep fat frying, consumer desired characteristics can be obtained in the end product (Roa and Delaney, 1995). Although this knowledge is known, much of the information is protected by patents. Thus various parameters for optimum processing for any type of food product is not available. This limits the use of this technology to a very few food products for which a method has been established. In addition, the existing pressure frying equipment depends on the moisture

released from the products to generate the pressure inside the fryer. As this method relies on a certain amount of moisture/steam to produce the desired pressure, the use of this equipment is also limited to a situation where a huge food load is fried in a single batch

The objective of this study was to evaluate the use of nitrogen for generating the required pressure in the fryer instead of using steam generated from moisture of the product. Experiments were conducted to study the effect of using nitrogen gas on the quality of fried chicken nuggets during pressure frying. The main objective of this study was to characterize the moisture retention and lipid uptake in fried foods as influenced by frying temperature, pressure, and source of pressure generation during deep fat frying.

MATERIALS AND METHODS

Sample Preparation

Commercial breaded chicken breast nuggets obtained from Purdue Farms Inc. were used in this study. All nugget components consisted of 14% breading and the meat block was formulated at a 83.67% ground chicken breast meat and skin, 15.23% water, 0.5% salt, 0.35% phosphate, and 0.25% seasoning. The chicken nuggets were prefried at 200°C for 25 s to set the breading system and then individually frozen. The nugget samples were kept in a freezer (approximately -40°C) until used for the experiment.

Frying Experiment

Experiments were conducted using commercial vegetable oil (Bakers & Chefs, North Arkansas Wholesale Company, Inc., Bentonville, AR) as the frying medium. The product samples were allowed to equilibrate to the ambient temperature (20°C) before frying. The samples were fried at three frying temperatures (150°C, 175°C and 190°C) and two pressures (163, and 184 kPa) using two sources of pressure, nitrogen gas or steam released from the food, to generate the required pressure in a restaurant-type pressure fryer (model 500C, Henney Penney, Inc., Eaton, OH). The pressure conditions

(163 and 184 kPa) were achieved by changing the specific dead weights and the fryer orifices in the operating valve.

The pressure fryer in this research was modified by adding a nitrogen gas flow system. The exhaust tube connected between operating valve and the frypot was replaced by a tee (T-shaped tube) for the flow of nitrogen gas (Fig. 3.1). The gas hose from the nitrogen gas tank was connected to a tee for supplying pressure at 240 kPa to the fryer vessel. After the pressure inside the fryer has reached the maximum setting controlled by the combination of the specific dead weights and the fryer orifices, a safety relief valve connected to the operating valve automatically released the excess pressure to the environment.

The other source of pressure used in this experiment was steam/moisture released from the food being fried. Pressure built-up in the fryer relied upon the amount of initial load, which was kept constant at 1200 g. A typical frying batch included 500 g of tested product and 700 g of fresh turkey breast added as the dummy load. Each treatment was fried at the same frying time of 240 s. A typical experiment included an average of 30 s delay in closing and opening the vessel. Every treatment was fried in three replications.

Finished Product Analyses

After frying, the chicken nugget samples were air cooled for 10 min and excessive surface oil was gently removed using tissue paper. The samples were placed in freezer bags and frozen at -40°C until further analysis.

Product Moisture and Fat Content

The appropriate procedure for separating the crust and core was developed with a preliminary test. The surface layer, defined as crust, was removed after careful visual inspection. The remaining portion was considered as core. The mass of the crust and core was recorded. The moisture content of the crust and core was determined using a freeze dryer (The Virtis Company, Inc., Gardiner, NY.). Freeze drying was selected over the traditional oven drying method because the freeze dryer preserved the porous

structure of the samples, which facilitated fat extraction during a subsequent fat analysis (Ateba and Mittal, 1994). The fat content of the freeze-dried samples was determined using AOAC method 960.39 (AOAC, 1995). The test was replicated three times.

Juiciness

Juiciness was measured using a press method described by Mallikarjunan and Mittal (1994). A set of filter papers (Whatman No.5, 15 cm diameter, Whatman International Ltd., Maidstone, UK.) was weighed and one gram of core was placed between two sheets of aluminum foil. This set of aluminum sheets was placed between filter papers and a set of Plexi-glass plates (15 x 15 cm). The sandwich was compressed by applying a 20 kPa pressure for 1 min. After pressing was completed, the sample along with the aluminum foils was discarded. The set of filter papers was reweighed to obtain the mass of pressed juice. The weight increase of the filter papers was correlated to the expressed juice from the product. The test was replicated three times.

Color Analysis

Color was measured using a chromameter (Model CR-300, Minolta Camera, Ltd., Osaka, Japan) calibrated to a white plate (CIE $L^* = 97.91$, $a^* = -0.68$, $b^* = 2.45$, part # 2093326) and the L^* , a^* and b^* values were used to calculate the derived color parameters. The test was replicated five times.

Breading Adhesion

The breading adhesion was calculated as described by Suderman and Cunningham (1983). Ten pieces of fried products were placed in a standard wire sieve (No. 4 US Sieve) and shaken for 1 min. The breadcrumbs that accumulated in the catch pan were weighed and the percentage of coating loss was calculated.

Texture

The texture of the fried samples was measured using a Kramer shear unit attached to a Sintech/MTS universal testing machine (model 5G, MTS, NC.). Speed of the Kramer shear unit was maintained at 100 mm/min. The peak load (N/kg), total energy (N.mm/kg) to peak load, and energy to failure point (N.mm/m³) were calculated to characterize the texture of the fried products. The test was replicated five times.

Statistical Analysis

Statistic analyses were performed using General Linear Model Program (GLM) to test the effects of frying temperature and pressure on chemical and physical characteristics of fried breaded chicken nuggets. Least Significant Difference (LSD) was used to estimate the significant differences among the means of each treatment at 5% the probability level using SAS program (SAS, 2000).

RESULTS AND DISCUSSION

The time to reach the pressure (163 kPa and 184 kPa) generated by using nitrogen gas was less than 5 s for both pressure conditions. On the other hand, the time to reach the desired pressure using steam released from foods ranged from 90 s to 195 s for the 163 kPa setting and 113 s to 230 s for 184 kPa. For frying under pressure generated by steam/moisture from the food, an increase in the frying oil temperature decreased the time needed to build-up the pressure to setting point. For oil temperature at 150°C, the pressure build-up was slower and it required about twice the time required for the other two oil temperatures.

In this study, it was found that the effects of frying temperature, pressure, and sources of pressure on breading adhesion of breaded chicken nuggets was not significantly different ($P>0.05$) and ranged from 1.33% to 2.24%.

Influence of Temperature and Pressure on Moisture

An increase in frying oil temperature significantly increased the moisture loss in both crust and core ($P < 0.05$). The crust moisture contents of products fried at 175°C and 190°C were 27.24% and 23.41%, respectively (Table 3.1). However, fried nuggets at 175°C and 190°C had similar core moisture content, but nuggets fried at 150°C had a significantly lower core moisture content. An increase in oil temperature during frying elevated the rate of dehydration of products and subsequently increased the removal of moisture. This result is consistent with the result found by Gamble et al. (1987).

As expected, an increase in pressure during frying resulted in a significant increase in moisture retention. Roa and Delaney (1995) and Mallikarjunan et al. (1995) also reported the same results. Products fried with steam at 163 and 184 kPa did not show a difference in crust and core moisture content. Compared with the traditional pressure frying, frying with nitrogen gas could be useful to prevent the moisture loss from the fried products.

Influence of Temperature and Pressure on Crust Fat Content

An increase in frying oil temperature resulted in a significant increase in oil uptake and surface fat content ($P < 0.05$) (Table 3.1). Mallikarjunan et al. (1995) also reported the same results. Fried products had a significantly decreased crust fat content as pressure during frying was increased ($P < 0.05$). Mallikarjunan et al. (1995) reported different results. The difference in results may be caused by a different batter and breading system used for the chicken nuggets. Batters and breadings can directly influence oil absorption (Duxbury, 1989). The batter coating apparently functioned to reduce water loss during frying which lessened oil absorption (Pinthus et al., 1993). Several studies have shown that oil uptake during deep fat frying of the food products is localized at the crust (Farkas et al., 1992; Gamble et al., 1987; Keller et al., 1986). In addition, a linear relationship between oil uptake and water removal was reported (Gamble et al., 1987). The initial and final moisture content has a major impact on oil uptake during deep fat frying (Gamble and Rice, 1988). Products fried with lower pressure resulted in a more open network of starch and protein in the breading system, and this 3-dimension network is porous. The voids mostly are filled with air and oil (Roa

and Delaney, 1995). The difference in crust fat content achieved by using nitrogen gas as opposed to steam was not significant ($P>0.05$).

Influence of Temperature and Pressure on Juiciness

An increase in frying oil temperature also decreased juiciness of fried nuggets ($P<0.05$). Fried nuggets at 175°C and 190°C did not have a difference in juice pressed from the core. In frying using steam, pressed juice at 163 kPa and 184 kPa were 31.58 and 33.85%, respectively (Table 3.1). The pressed juice (obtained from using nitrogen) at 163 kPa and 184 kPa were 6.8% and 1.9%, higher than that of steam, respectively. Frying with nitrogen gas increased more juice in the core than the steam system. The interaction effect of frying pressure and oil temperature on pressed juice was not significant.

Influence of Temperature and Pressure on Color of Fried Foods.

As expected, an increase in frying temperature resulted in significant changes ($P<0.05$) in crust color (Table 3.2). The crust became significantly darker. The color changes are confirmed by an increase in a^* value and the reduction of L^* and b^* values. Several chemical reactions during frying including denaturation of protein, gelatinization of starch, and browning reaction of batter and breading system. All these reactions affect crust color changes.

Increasing pressure and the change of source to generate pressure did not affect crust color ($P>0.05$). There were no significant differences in core L^* (light) and b^* (yellow) color by changing frying temperature and pressure during deep fat frying (Table 3.2). On the other hand, increasing frying oil temperature resulted in less red core color of fried food ($P<0.05$) due to greater heat penetrated into the interior of the products.

Influence of Temperature and Pressure on Texture of Fried Nuggets

An increase in frying oil temperature resulted in a significant increase ($P<0.05$) to peak force, energy to peak force and total energy to failure point (Table 3.3). Fried products were harder and tougher as oil temperature increased. The elevation of oil

temperature provided substantial heat transported to the product surface and then changed crust texture.

Increasing the frying pressure resulted in a significant decrease ($P < 0.05$) in energy to peak force and total energy to failure point per volume (Table 3.3). An increase in pressure did not affect peak force. However, the peak force tended to decrease with higher pressure applied during frying. Commonly, frying under pressure is known to produce fried products more tender and juicy (Roa and Delaney, 1995; Mallikarjunan et al., 1995). In addition, Roa and Delaney (1995) found that positive pressure during frying imparted a softer texture to the breading, while use of atmospheric pressure resulted in a crispy texture. Lower pressures during frying produced a more open starch-protein network, more porosity in crust, and more increase in continuity of the starch granules, resulting in a less moisture in crust portion, brittle and fluffy in texture (Roa and Delaney, 1995). From these reasons, the applied force to shear the fried products was higher for lower pressure used during frying. Frying using nitrogen gas resulted in a significantly lower ($P < 0.05$) energy to peak force, and total energy to failure point per volume than the use of steam released from foods (Table 3.3). These results may cause due to more moisture retention, softer crust, and an overall more tender and juicy product.

CONCLUSIONS

The use of nitrogen gas as a pressurizing medium during deep fat frying instead of steam released from the food increased the moisture retention (both in crust and core) and elevated the pressed juice ($p < 0.05$). In addition, frying using nitrogen gas provided a tender product than the use of steam, as measured by a significantly lower energy to peak force, and total energy to failure point ($p < 0.05$). Compared with the use of steam released from the food, frying under nitrogen gas provided similar or better quality of fried products in terms of moisture retention, juiciness, and texture. An increase in applied pressure applied in frying process increased the moisture content, pressed juice inside the fried foods, and reduced oil uptake. On the other hand, an increase in frying oil temperature increased the moisture loss, crust oil uptake, and hardened the texture ($p < 0.05$).

REFERENCES

- AOAC. 1995. Official Methods of Analysis of AOAC International. 16th edition, vol. 2, Arlington, Virginia.
- Ateba, P. and Mittal, G.S. 1994. Modeling the deep-fat frying of beef meatballs. *Intl. J. Food Sci. Technol.* 29: 429-440.
- Duxbury, D.D. 1989. Oil water barrier properties enhanced in fried foods, batters. *Food Proc.* 50(2): 66-69.
- Farkas, B.E., Singh, R.P., and McCarthy, M.J. 1992. Determination of oil/water distribution within fried foods. Presented at the Annual Meeting of the Inst. of Food Technologists, New Orleans, LA.
- Gamble, M.H. and Rice, P. 1988. The effect of slice thickness on potato crisp yield and composition. *J. Food Eng.* 8: 31-46.
- Gamble, M.H., Rice, P., and Selman, J.D. 1987. Relationship between oil uptake and moisture loss during frying potato slices from c.v. Record UK. Tubers. *Intern. J. Food Sci. and Technol.* 22: 233-241.
- Guillaumin, R. 1988. Kinetics of fat penetration in food. in "*Frying of food*", p. 82-90. G. Varela, A.E. Bender and I.D. Morton (Ed.), Ellis Horwood Ltd., Chichester, England.
- Keller, C.H., Escher, F., and Solms, J.A. 1986. Method for localizing fat distribution in deep-fried potato products. *Lebensmittel-Wiss. U. Technol.* 19(4): 346-348.
- Lamberg, I., Hallstrom, B. and Olsson, H. 1990. Fat uptake in a potato drying/frying process. *Lebensm-Wiss. U. Technol.* 23: 295-300.
- Mallikarjunan, P. and Mittal, G.S. 1994. Meat quality kinetics during beef carcass chilling. *J. Food Sci.* 59: 291-294, 302.
- Mallikarjunan, P., Chinnan, M.S. and Balasubramaniam, V.M. 1995. Mass transfer in edible film coated chicken nugget: influence of frying temperature and pressure. *CoFE.* 107-111.
- Orthoefer, F.T. and Cooper, D.S. 1996. Evaluation of used frying oil. Ch. 16 in "*Deep frying. Chemistry, nutrition, and practical applications*". E.G. Perkins and M.D. Erickson (Ed.), p.285-296. AOCS Press, Champaign, IL.

- Pinthus, E.J., Weinberg, P., and Saguy, I.S. 1993. Criterion for oil uptake during deep-fat frying. *J. Food Sci.* 58(1): 204-205, 222.
- Roa, V.N.M. and Delaney, A.M. 1995. An engineering perspective on deep-fat frying of breaded chicken pieces. *Food Technol.* 49(4): 138-141.
- SAS Institute, 2000. SAS Institute Inc., Cary, NC.
- Stevenson, S.G., Vaisey-Genser, M. and Eskin, N.A.M. 1984. Quality control in the use of deep frying oils. *J. Am. Oil Chemists' Soc.* 61(6): 1102-1108.
- Suderman and Cunningham, 1983. *Batter and Breading*. AVI Pub. Co., Westport, CT. 224 p.
- Tseng, Y.C., Moreira, R.G., and Sun, X. 1994. Physical and chemical properties of oil degradation related to food quality in deep-fat frying. Paper No. 94- 6524. Presented at 1994 International Winter Meeting of ASAE, Atlanta, GA. Dec 13-16.
- Varela, G. 1988. Current facts about the frying of food. Ch. 1 in "*Frying of food*", p. 9-25. G. Varela, A.E. Bender and I.D. Morton (Ed.), Ellis Horwood Ltd., Chichester, England.

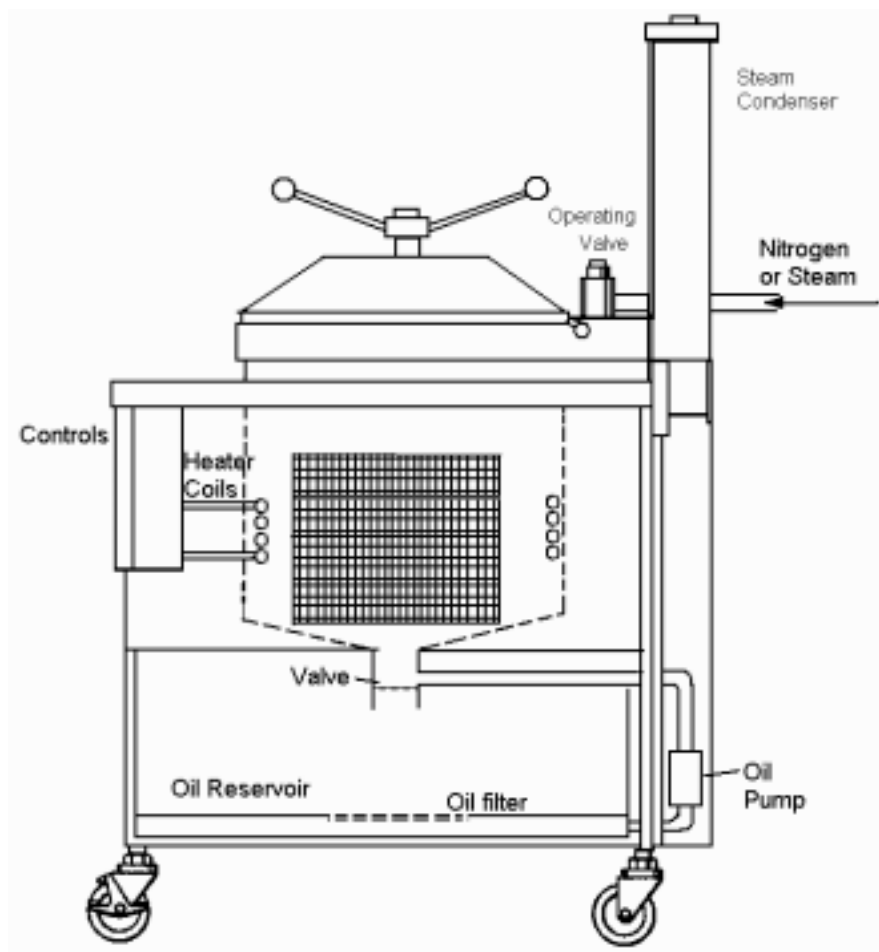


Figure 3.1 Modification of pressure fryer used in this research

Table 3.1 Mean moisture content, crust fat content, and juiciness for different frying parameters.

Effect of temperature

Temperature (°C)	Moisture ¹ (%)		Crust Fat ¹ (%)	Juiciness ¹ (%)
	Crust	Core		
150	32.93 ^a	63.83 ^a	21.78 ^a	35.35 ^a
175	27.24 ^b	61.85 ^b	23.32 ^b	32.81 ^b
190	23.41 ^c	61.65 ^b	25.13 ^c	32.09 ^b

Effect of pressure

Source of pressure	Pressure (kPa)	Moisture ² (%)		Crust Fat ² (%)	Juiciness ² (%)
		Crust	Core		
steam	163	26.77 ^a	62.24 ^a	23.89 ^a	31.58 ^a
steam	184	28.06 ^{ab}	62.26 ^a	23.08 ^b	33.85 ^b
nitrogen	163	27.06 ^a	62.57 ^b	23.68 ^a	33.74 ^b
nitrogen	184	29.55 ^b	62.70 ^c	22.98 ^b	34.49 ^c

¹ n = 45

² n = 27

^{abc} means within a column with unlike superscript letters are significantly different (P<0.05).

Table 3.2 Mean crust color and core color for different frying parameters.

Effect of temperature

Temperature (°C)	Crust ¹			Core ¹		
	L*	a*	b*	L*	a*	b*
150	58.92 ^a	9.30 ^a	48.31 ^a	76.96 ^a	-1.21 ^a	23.74 ^a
175	50.25 ^b	12.51 ^b	43.65 ^b	76.69 ^a	-0.93 ^b	23.38 ^a
190	40.00 ^c	16.83 ^c	35.03 ^c	76.64 ^a	-1.45 ^c	23.93 ^a

Effect of pressure

Source of pressure	Pressure (kPa)	Crust ²			Core ²		
		L*	a*	b*	L*	a*	b*
steam	163	49.67 ^a	12.22 ^a	41.87 ^a	76.50 ^a	-1.35 ^a	23.59 ^a
steam	184	48.22 ^a	13.37 ^a	41.98 ^a	76.86 ^a	-1.36 ^a	23.58 ^a
nitrogen	163	50.97 ^a	12.91 ^a	42.97 ^a	76.86 ^a	-1.16 ^{ab}	23.45 ^a
nitrogen	184	50.01 ^a	13.00 ^a	42.50 ^a	76.83 ^a	-0.93 ^b	24.10 ^a

¹ n = 75

² n = 45

^{abc} means within a column with unlike superscript letters are significantly different

(P<0.05).

Table 3.3 Mean peak force, energy to peak force, and total energy to failure point for different frying parameters.

Effect of temperature

Temperature (°C)	Peak force ¹ x 10 ³ (N/kg)	Energy to peak force ¹ x 10 ³ (N.mm/kg)	Total energy to failure point ¹ x 10 ⁶ (N.mm/m ³)
150	17.63 ^a	85.34 ^a	42.47 ^a
175	23.59 ^b	142.61 ^b	52.84 ^b
190	28.72 ^c	154.58 ^c	63.60 ^c

Effect of pressure

Source of Pressure	Pressure (kPa)	Peak force ² x 10 ³ (N/kg)	Energy to peak force ² x 10 ³ (N.mm/kg)	Total energy to failure point ² x 10 ⁶ (N.mm/m ³)
steam	163	23.57 ^a	136.14 ^b	55.11 ^c
steam	184	23.46 ^a	141.85 ^c	53.76 ^b
nitrogen	163	23.51 ^a	128.07 ^b	52.21 ^b
nitrogen	184	22.70 ^a	103.97 ^a	50.79 ^a

¹ n = 75

² n = 45

^{abc} means within a column with unlike superscript letters are significantly different (P<0.05).

CHAPTER 4

The Effect of Pressure Conditions on Quality of Chicken Nuggets Fried with Constant Core Temperature

ABSTRACT

The traditional pressure frying has been limited due to its dependence on the amount of moisture/steam released from the fried products for generating the required pressure. Thus, the use of this equipment is controlled by the situation where a large food load is fried. The objectives of this study address the use of nitrogen gas for generating the required pressure in the fryer instead of using steam released from the product. The effects of frying temperature and pressure on product quality were evaluated. Chicken nuggets were fried at three frying temperatures (150°C, 175°C, and 190°C) and pressures (101, 163, and 184 kPa) in a restaurant-type pressure fryer. The fryer was modified so that external gas could be introduced to pressurize the frying vessel.

Frying temperature and pressure directly affected the fried food quality. As expected, an increase in pressure during frying resulted in a significant increase in moisture retention and juiciness of fried products ($P < 0.05$). Frying with nitrogen gas produced fried products that had more moisture retention, and thus more juice was pressed from the core than frying with steam and atmospheric frying, respectively. The product fried under nitrogen gas was tender as measured by a significantly lower peak force, energy to peak force, and total energy to failure point ($P < 0.05$). An increase in the frying oil temperature increased the moisture loss and oil uptake in the crust, and the fried products were less tender and juicy ($P < 0.05$).

Keywords: pressure frying, nitrogen gas, steam, chicken nuggets, moisture retention, oil uptake.

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INTRODUCTION

Frying is considered to be one of the oldest thermal processing techniques in existence (Varela et al., 1988). It is widely used by the multimillion-dollar snack food industry. The immersion frying process is also called deep fat frying, which generates foods with a unique, attractive and crispy surface texture with rich flavors and aromas. The soft and moist interior along with the porous outer crispy crust provides a desirable palatability (Orthoefer et al., 1996; Varela, 1988).

Deep fat frying involves simultaneous heat and mass transfers. Convective heat transfer takes place between the surrounding oil and the foods at the food surface and heat penetrates to the interior of the food product by conduction (Singh, 1995). Several chemical and physical changes take place during frying including starch gelatinization, protein denaturation, water vaporization, and crust formation (Saguy and Pinthus, 1995). In addition, the two main modes of mass transfer that occur during food frying are moisture loss and oil uptake by the foods.

Research has focused on different aspects of the frying operation to obtain a better understanding of the process. Many researchers have studied the relationship between oil uptake and moisture loss during frying (Roa and Delaney, 1995; Mallikarjunan et al., 1995). The considerable amount of work done on deep fat frying has been primarily focused on non-fatty foods such as french fries, tortilla chips, and snack products. Research on deep fat frying of breaded chicken parts has been limited, and most has been a result of trying to develop a new product or process.

Pressure frying provides food products that are more juicy and tender than products fried at atmospheric pressure (Roa and Delaney, 1995; Mallikarjunan et al., 1995). By suitably selecting pressure and temperature, consumer desirable characteristics can be obtained in the end product (Roa and Delaney, 1995). The effects of frying parameters such as pressure, temperature, and frying time for optimum deep fat frying of specific fried products is still unknown. Thus, the use of this technology is limited to a very few food products for which a method has been defined. In addition, both industrial and food service pressure-frying equipment depends on the amount of moisture/steam

released from the products to generate the required pressure. The use of this equipment is controlled by the situation where a large food load is fried in one batch.

The primary focus of this study was to use nitrogen gas for generating the required pressure in the fryer instead of using steam released from the food. Experiments were conducted to study the effect of using nitrogen gas to supply the desired pressure on fried chicken nuggets. The main objective of this study was to characterize the moisture retention and the reduction in oil uptake in fried foods as influenced by frying temperature, pressure, and source of pressure generation during deep fat frying.

MATERIALS AND METHODS

Sample Preparation

Commercial breaded chicken breast nuggets obtained from Tyson Company, Inc. were used in this study. All nugget samples were individually frozen and had the same production date. The nugget samples were kept in a freezer (approximately -40°C) until needed for the frying experiment.

Frying Experiment

Experiments were conducted using commercial vegetable oil (Bakers & Chefs, North Arkansas Wholesale Company, Inc., Bentonville, AR) as the frying medium. The product samples were allowed to equilibrate to the ambient temperature (20°C) before frying. The samples were fried at three frying temperatures (150°C , 175°C and 190°C) and three pressures (101 kPa, 163 kPa, and 184 kPa) using two sources of pressure, nitrogen gas or steam released from the food, to generate the required pressure in a restaurant-type pressure fryer (model 500C, Henney Penney, Inc., Eaton, OH). The pressure setting at 101 kPa referred to frying at atmospheric pressure. The pressure conditions (163 and 184 kPa) were achieved by changing the specific dead weights and the fryer orifices in the operating valve. The pressure fryer in this research was modified by adding a nitrogen gas flow system (Innawong et al., 2001).

The other source of pressure used in this experiment was steam/moisture released from the food being fried. Thus, pressure built-up in the fryer relied upon the amount of initial load, which was kept constant at 1200 g. A typical frying batch included 500 g of tested product and 700 g of fresh turkey breast added as the dummy load. The temperatures at the surface and at the geometric center of the fried samples were monitored using a T-type 30 gage thermocouple (TT-T-30, Omega Engineering, Stamford, CT) attached to an electronic temperature recorder (model 5100, ACR data logger, Omega Engineering, Inc., Stamford, CT). The frying oil temperature in the vicinity of the samples was also monitored. The maximum frying period was selected so that at the end of frying, the geometric center of the products reached 70°C or above. A typical experiment included an average of 30 s delay in closing and opening the vessel. Every treatment was replicated three times.

Finished Product Analyses

After frying, the chicken nugget samples were air cooled for 10 min and excessive surface oil was gently removed using tissue paper. The samples were placed in freezer bags and frozen at -40°C until further analysis.

Product Moisture and Fat Content

The appropriate procedure for separating the crust and core was developed with a preliminary test. The surface layer, defined as crust, was removed after careful visual inspection. The remaining portion was considered as core. The mass of the crust and core was recorded. The moisture content of the crust and core was determined using a freeze dryer (The Virtis Company, Inc., Gardiner, NY.). Freeze drying was selected over the traditional oven drying method because the freeze dryer preserved the porous structure of the samples, which facilitated fat extraction during a subsequent fat analysis (Ateba and Mittal, 1994). The fat content of the freeze-dried samples was determined using AOAC method 960.39 (AOAC, 1995). The test was replicated three times.

Juiciness

Juiciness was measured using a press method described by Mallikarjunan and Mittal (1994). A set of filter papers (Whatman No.5, 15 cm diameter, Whatman International Ltd., Maidstone, UK.) was weighed and one gram of core was placed between two sheets of aluminum foil. This set of aluminum sheets was placed between filter papers and a set of Plexi-glass plates (15 x 15 cm). The sandwich was compressed by applying a 20 kPa pressure for 1 min. After pressing was completed, the sample along with the aluminum foils was discarded. The set of filter papers was reweighed to obtain the mass of pressed juice. The weight increase of the filter papers was correlated to the expressed juice from the product. The test was replicated three times.

Color Analysis

Color was measured using a chromameter (Model CR-300, Minolta Camera, Ltd., Osaka, Japan) calibrated to a white plate (CIE $L^* = 97.91$, $a^* = -0.68$, $b^* = 2.45$, part # 2093326) and the L^* , a^* and b^* values were used to calculate the derived color parameters. The test was replicated five times.

Breading Adhesion

The breading adhesion was calculated as described by Suderman and Cunningham (1983). Ten pieces of fried products were placed in a standard wire sieve (No. 4 US Sieve) and shaken for 1 min. The breadcrumbs that accumulated in the catch pan were weighed and the percentage of coating loss was calculated.

Texture

The texture of the fried samples was measured using a Kramer shear unit attached to a Sintech/MTS universal testing machine (model 5G, MTS, NC.). Speed of the Kramer shear unit was maintained at 100 mm/min. The peak load (N/kg), total energy

(N.mm/kg) to peak load, and energy to failure point (N.mm/m³) were calculated to characterize the texture of the fried products. The test was replicated five times.

Statistical Analysis

Statistic analyses were performed using General Linear Model Program (GLM) to test the effects of frying temperature and pressure on chemical and physical characteristics of fried breaded chicken nuggets. Least Significant Difference (LSD) was used to estimate the significant differences among the means of each treatment at 5% the probability level using SAS program (SAS, 2000).

RESULTS AND DISCUSSION

Increasing the temperature of the frying medium decreased the time needed to build up pressure to the set-point and also reduced cooking time to reach 70°C at the geometric center of the fried products (Fig. 4.1). By using nitrogen gas to create the desired pressure in the fryer chamber, it seemed to reduce frying time when compared to use of steam (Fig. 4.1). Increasing the pressure from 101 kPa (atmospheric frying) to 163 kPa increased frying time for frying oil temperature of 175°C and 190°C. On the other hand, increasing pressure from 163 kPa to 184 kPa did not change the frying time significantly (Fig. 4.1). However, the frying time of the products fried in the system using steam generated pressure relied on the amount of initial load but the use of nitrogen gas was more convenient and independent on frying load.

Influence of Temperature and Pressure on Moisture

An increase in the frying oil temperature resulted in a significant increase in moisture loss from the crust ($P<0.05$). However, the core retained more moisture ($P<0.05$). The moisture content of the crust at 175°C and 190°C were 33.5% and 31.43%, respectively, and the core moisture content at 175°C and 190°C were 68.2% and 68.49%, respectively (Table 4.1). The crust moisture content decreased 14.3% at 175°C

and 19.6% at 190°C as compared with crust moisture at 150°C. On the other hand, the core moisture content increased approximately 0.5% at 175°C and 1.0% at 190°C as compared with crust moisture at 150°C. The cause of the reduction in core moisture may be that the product stayed longer in the fryer when fried at lower oil temperature.

However, the exterior of the nuggets directly contacted to hot oil caused a more rapid dehydration at higher oil temperature. This resulted in a significant decrease in moisture content of the crust. On the other hand, the breading on a fried chicken nugget acted as a moisture barrier to diffusion of water vapor from inside and thereby contributed to a juicier core. Gamble et al. (1987) proposed the mechanism of moisture transfer from the interior of the food during frying. As the food materials undergo frying, the inner moisture is converted to water vapor causing a pressure gradient and the vapors escape at the weak points in the fried food surface (Gamble et al., 1987).

As expected, an increase in pressure during frying resulted in a significant reduction in the moisture loss (Table 4.1). Roa and Delaney (1995) and Mallikarjunan et al. (1995) also reported the same results. It is known that using positive pressure during frying imparts a softer texture to the breading, while use of atmospheric pressure (101 kPa) resulted in a crispy texture (Roa and Delaney, 1995). Frying with nitrogen gas increased moisture retention as compared to frying with steam. There were no significant differences in moisture contents and juiciness for frying with steam and nitrogen gas at 163 kPa and 184 kPa.

Influence of Temperature and Pressure on Juiciness

An increase in frying oil temperature increased juiciness of nugget samples ($P < 0.05$). Fried nuggets at 175°C and 190°C did not show a difference in juiciness but both had significantly higher juiciness than nuggets fried at 150°C (Table 4.1). As expected, an increase in pressure resulted in a significant increase ($P < 0.05$) in juiciness in the core more than atmospheric pressure (Table 4.1). The products fried with nitrogen gas retained more pressed juice than the ones fried with steam and atmospheric frying, respectively. For example, frying with nitrogen gas at 184 kPa increased pressed juice about 5% compared with steam at 184 kPa and 17% compared with atmospheric frying.

Influence of Temperature and Pressure on Crust Fat Content

As expected, an increase in frying oil temperature significantly increased ($P < 0.05$) oil uptake of the crust (Table 4.1). Fat content of the crust was not significantly different for frying at oil temperatures 175°C and 190°C. Mallikarjunan et al. (1995) also reported that higher frying oil temperature resulted in an increase oil uptake and surface fat content. Several studies deal with the relationship between moisture content and oil uptake (Gamble et al., 1987; Gamble and Rice, 1988). Gamble et al. (1987) presented a linear relationship between oil uptake and water removal. In addition, the initial and final water content has a major impact on oil uptake during deep fat frying (Gamble and Rice, 1988). Normally, oil simply replaces moisture lost during frying.

The effect of frying pressure on oil uptake in the crust was significant ($P < 0.05$). Increasing the frying pressure during frying resulted in decreased oil uptake (Table 4.1). Several studies have shown that oil uptake during deep fat frying of the food products is localized at the crust (Farkas et al., 1992; Gamble et al., 1987; Keller et al., 1986). Lower pressures during frying resulted in an open network of starch and protein. This three dimensional network was porous with the voids mostly filled with air and oil (Roa and Delaney, 1995).

Influence of Temperature and Pressure on Color of Fried Chicken Nuggets

As expected, an increase in frying oil temperature resulted in significant changes ($P < 0.05$) in crust color (Table 4.2). Fried chicken nuggets was significantly darker when fried at higher oil temperature as confirmed by an increase in L^* value and a decrease in a^* value. The changes of crust color during frying were due to several chemical reactions including protein denaturation, starch gelatinization, and browning reaction in the batter and breading. There was no significant difference in core color by changing frying temperature (Table 4.2). Frying under pressure resulted in a redder core color than atmospheric pressure (Table 4.2). With the same source of pressure, there were no differences in crust and core colors at 163 kPa and 184 kPa. Based on L^* value, product

fried with nitrogen gas was significantly darker in appearance than product fried with steam.

Influence of Temperature and Pressure on Texture of Fried Nuggets

An increase in frying oil temperature resulted in a significant reduction ($P < 0.05$) in bulk density (Table 4.3). An increase in oil temperature increased the porosity of fried products due to the removal of water during frying. The frying pressure also affected bulk density of the fried nuggets (Table 4.3). In this experiment, the bulk density of chicken nuggets fried at atmospheric pressure was 959.1 kg/m^3 , which was the lowest value obtained for all treatments. There was no significant difference in bulk density for nuggets fried with nitrogen gas at 163 kPa and 184 kPa. On the other hand, bulk density of fried nuggets increased as pressure generated by steam increased. An increase in the oil temperature resulted in a significant decrease in breading adhesion ($P < 0.05$). But an increase in frying pressure and change in pressure source did not affect breading adhesion (Table 4.3).

Increasing frying oil temperature resulted in a significant increase ($P < 0.05$) in peak force, energy to peak force, and total energy to failure point (Table 4.3). The texture of the products fried at higher oil temperature was harder and tougher than the products fried at lower oil temperature. As the oil temperature increased, the rate of heat transfer also increased, and subsequently the surface hardened due to crust formation, protein denaturation, and starch gelatinization.

An increase in pressure resulted in a significant reduction ($P < 0.05$) in peak force, energy to peak force, and total energy to failure point (Table 4.3). Frying under pressure is known to produce more tender and juicier fried products (Roa and Delaney, 1995; Mallikarjunan et al., 1995). In addition, Roa and Delaney (1995) found that using positive pressure during frying imparted a softer texture to the breading, while use of atmospheric pressure resulted in a crispy texture. Lower pressures during frying produced a more open starch-protein network, more crust porosity, and more continuity of the starch granules (Roa and Delaney, 1995). Thus, the fried product had less moisture in the crust, and was brittle and fluffy in texture. The products fried under lower pressure

needed more force and energy needed to shear the products fried at atmospheric pressure. There was no difference in energy to peak force and total energy to failure point as pressure generated by steam increased from 163 to 184 kPa. The effect of the pressure source on peak force was measured. Frying with nitrogen gas had significant ($P < 0.05$) lower energy to peak force and total energy to failure point than frying with steam (Table 4.3) because the products fried with nitrogen gas had more moisture retention, more juiciness, and were tender in texture than the products fried with steam. However, there was no difference in peak force between 163 and 184 kPa with the same source of pressure.

CONCLUSIONS

Frying temperature and pressure directly affected the fried food quality. An increase in pressure provided more moisture retention in crust and core and also juicier fried products than atmospheric frying ($P < 0.05$). The nuggets fried with nitrogen gas had more moisture retention, and pressed juice in core than the nuggets fried with steam. In addition, the nuggets fried with nitrogen gas were tender and not as hard as nuggets fried with steam as measured by significantly lowered peak force, energy to peak force, and total energy to failure point ($P < 0.05$). An increase in the frying oil temperature increased the moisture loss and oil uptake in the crust, and the fried products were less tender and juicy ($P < 0.05$).

REFERENCES

- AOAC. 1995. Official Methods of Analysis of AOAC International. 16th edition, vol. 2, Arlington, Virginia.
- Ateba, P. and Mittal, G.S. 1994. Modeling the deep-fat frying of beef meatballs. *Intl. J. Food Sci. Technol.* 29: 429-440.
- Farkas, B.E., Singh, R.P., and McCarthy, M.J. 1992. Determination of oil/water distribution within fried foods. Presented at the Annual Meeting of the Inst. of Food Technologists, New Orleans, LA.
- Gamble, M.H. and Rice. P. 1988. The effect of slice thickness on potato crisp yield and composition. *J. Food Eng.* 8: 31-46.
- Gamble, M.H., Rice, P., and Selman, J.D. 1987. Relationship between oil uptake and moisture loss during frying potato slices from c.v. Record UK. Tubers. *Intern. J. Food Sci. and Techn.* 22: 233-241.
- Innawong, B., Mallikarjunan, P., and Cundiff, J.S. 2001. The effect of pressure conditions on quality of chicken nuggets fried with constant frying time. (In Preparation).
- Keller, Ch., Escher, F., and Solms, J.A. 1986. Method for localizing fat distribution in deep-fried potato products. *Lebensmittel-Wiss. U. Technol.* 19(4): 346-348.
- Mallikarjunan, P. and Mittal, G.S. 1994. Meat quality kinetics during beef carcass chilling. *J. Food Sci.* 59: 291-294, 302.
- Mallikarjunan, P., Chinnan, M.S. and Balasubramaniam, V.M. 1995. Mass transfer in edible film coated chicken nugget: influence of frying temperature and pressure. *CoFE.* 107-111.
- Orthoefer, F.T. and Cooper, D.S. 1996. Evaluation of used frying oil. Ch. 16 in "*Deep frying. Chemistry, nutrition, and practical applications*". E.G. Perkins and M.D. Erickson (Ed.), p. 285-296. AOCS Press, Champaign, IL.
- Roa, V.N.M. and Delaney, A.M. 1995. An engineering perspective on deep-fat frying of breaded chicken pieces. *Food Technol.* 49(4): 138-141.
- Saguy, I.S. and Pinthus, E.J. 1995. Oil uptake during deep-fat frying: Factors and mechanism. *Food Technol.* 49(4): 142-145, 152.

SAS Institute, 2000. SAS Institute Inc., Cary, NC.

Singh, R.P. 1995. Heat and mass transfer in foods during Deep-fat frying. *Food Technol.* 49(4): 134-137.

Suderman and Cunningham, 1983. *Batter and Breading*. AVI Pub. Co., Westport, CT. 224p.

Varela, G. 1988. Current facts about the frying of food. Ch. 1 in "*Frying of food*", p. 9-25. G. Varela, A.E. Bender and I.D. Morton (Ed.), Ellis Horwood Ltd., Chichester, England.

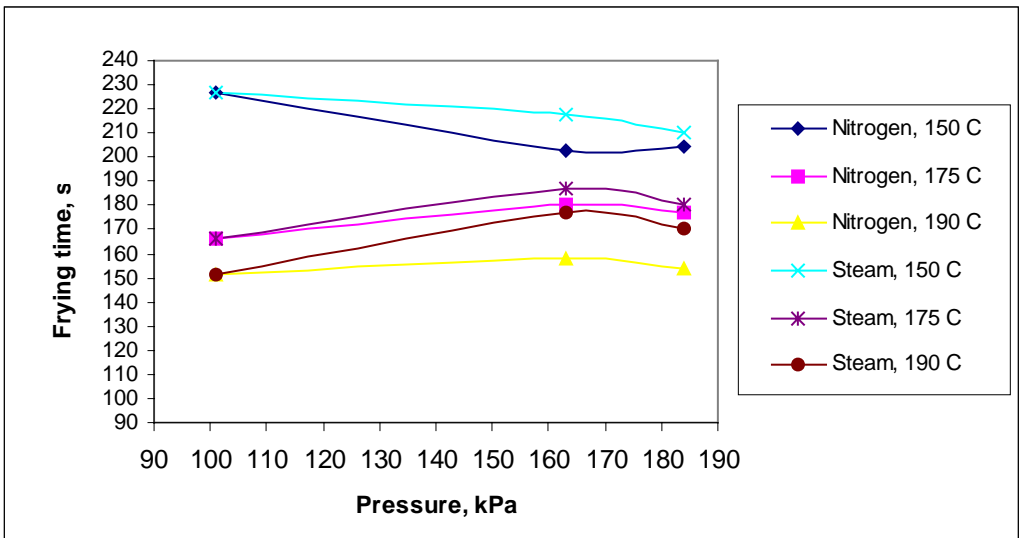
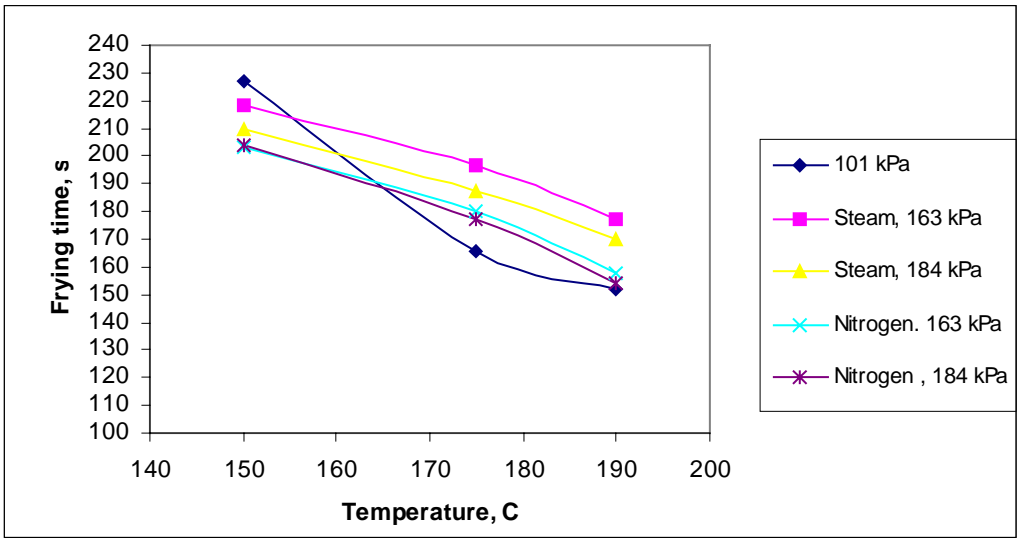


Figure 4.1 Frying time to reach 70°C at the geometric center of chicken nuggets.

Table 4.1 Mean moisture content, crust fat content, and juiciness for different frying parameters.

Effect of temperature

Temperature (°C)	Moisture ¹ (%)		Crust Fat ¹ (%)	Juiciness ¹ (%)
	Crust	Core		
150	39.10 ^a	67.90 ^a	17.45 ^a	29.67 ^a
175	33.50 ^b	68.20 ^b	19.00 ^b	31.15 ^b
190	31.43 ^c	68.49 ^c	19.53 ^b	33.68 ^b

Effect of pressure

Source of pressure	Pressure (kPa)	Moisture ² (%)		Crust Fat ² (%)	Juiciness ² (%)
		Crust	Core		
atmosphere	101	32.34 ^a	67.31 ^a	19.93 ^a	28.44 ^a
steam	163	34.79 ^b	68.05 ^b	18.44 ^b	31.44 ^b
steam	184	34.98 ^b	68.13 ^b	17.95 ^c	31.74 ^b
nitrogen	163	35.30 ^c	68.51 ^{bc}	19.00 ^{ab}	32.57 ^c
nitrogen	184	35.97 ^c	68.97 ^c	17.96 ^c	33.30 ^c

¹ n = 45

² n = 27

^{abc} means within a column with unlike superscript letters are significantly different (P<0.05).

Table 4.2 Mean crust color and core color for different frying parameters.

Effect of temperature

Temperature (°C)	Crust ¹			Core ¹		
	L*	a*	b*	L*	a*	b*
150	60.92 ^a	7.45 ^a	40.28 ^a	76.43 ^a	3.72 ^a	14.59 ^a
175	55.26 ^b	11.78 ^b	42.49 ^b	77.08 ^a	3.58 ^a	14.78 ^a
190	49.55 ^c	15.96 ^c	42.21 ^b	77.17 ^a	3.62 ^a	14.79 ^a

Effect of pressure

Source of pressure	Pressure (kPa)	Crust ²			Core ²		
		L*	a*	b*	L*	a*	b*
atmosphere	101	58.90 ^a	10.49 ^a	41.83 ^a	76.86 ^a	3.39 ^a	15.37 ^a
steam	163	54.33 ^b	12.34 ^b	42.08 ^a	77.08 ^a	3.59 ^b	14.65 ^{bc}
steam	184	54.01 ^b	12.61 ^b	41.91 ^a	76.88 ^a	3.70 ^b	15.06 ^{ab}
nitrogen	163	55.62 ^c	11.57 ^c	41.57 ^{ab}	77.23 ^a	3.65 ^b	14.31 ^c
nitrogen	184	55.36 ^c	11.64 ^c	40.89 ^b	76.41 ^a	3.87 ^b	14.22 ^c

¹ n = 75

² n = 45

^{abc} means within a column with unlike superscript letters are significantly different

(P<0.05).

Table 4.3 Mean density, breading adhesion, peak force, energy to peak force, and total energy to failure point for different frying parameters.

Effect of temperature

Temperature (°C)	Density ¹ (kg/m ³)	Breading ¹ adhesion (%)	Peak force ² x 10 ³ (N/kg)	Energy to peak force ² x 10 ³ (N.mm/kg)	Total energy to failure point ² x 10 ⁶ (N.mm/m ³)
150	1040.4 ^a	1.23 ^a	15.57 ^a	112.92 ^a	23.67 ^a
175	959.4 ^b	0.62 ^b	21.69 ^b	149.96 ^b	29.13 ^b
190	910.8 ^c	0.76 ^b	24.34 ^c	170.37 ^c	32.00 ^c

Effect of pressure

Source of Pressure	Pressure (kPa)	Density ³ (kg/m ³)	Breading ³ adhesion ³ (%)	Peak force ⁴ x 10 ³ (N/kg)	Energy to peak force ⁴ x 10 ³ (N.mm/kg)	Total energy to failure point ⁴ x 10 ⁶ (N.mm/m ³)
atmosphere	101	959.1 ^a	0.67 ^a	22.81 ^a	160.85 ^a	31.19 ^a
steam	163	972.9 ^b	0.86 ^a	20.38 ^b	146.38 ^b	29.22 ^b
steam	184	964.0 ^a	0.97 ^a	20.26 ^b	143.46 ^b	28.05 ^b
nitrogen	163	977.4 ^b	0.77 ^a	19.85 ^c	140.78 ^b	27.24 ^b
nitrogen	184	981.0 ^b	1.09 ^a	19.35 ^c	130.61 ^c	25.63 ^c

¹ n = 45

² n = 27

³ n = 75

⁴ n = 45

^{abc} means within a column with unlike superscript letters are significantly different

(P<0.05).

CHAPTER 5

The Effect of Pressure Conditions on Quality of Chicken Fillets Cooked for Doneness

ABSTRACT

The effect of using nitrogen gas instead of steam released from the food being fried to produce pressure was investigated. Industrial and food service pressure frying equipment heavily depends on the frying load to create the desired pressure. In this study, nitrogen gas was used as a source for generating the pressure to overcome this limitation. The effects of frying temperature, pressure, and pressure source on product quality were evaluated.

Chicken fillets were fried at three frying temperatures (150°C, 175°C, and 190°C) and three pressures (101, 163, and 184 kPa) in a restaurant-type pressure fryer. Frying temperature, pressure, and the source of pressure directly affected on fried food quality. Frying with nitrogen gas produced a higher moisture retention in crust and core and produced juicier fried products than frying with steam ($P<0.05$). The product fried with nitrogen gas was tender and not as hard as product fried with steam and atmospheric pressure, respectively, as determined by a significantly lower peak force, energy to peak force, and total energy to failure point ($P<0.05$). An increase in frying oil temperature resulted in a higher moisture loss and oil uptake in the crust, and the fried products were harder, tougher, and less juicy ($P<0.05$).

Keywords: pressure frying, nitrogen gas, steam, chicken fillets, moisture retention, oil uptake

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INTRODUCTION

Frying is a complex and important operation that is commonly used in the industrial or institutional preparation of foods (Varela, 1988). The frying process combines a heat treatment at high moisture with dehydration to form a dry crust with porous structure and crisp texture, and the product interior remains soft and moist. These unique characteristics make fried foods palatable and popular. Having an attractive and tasty product surface, frying is a very popular method for thermally processing foods. In the United States, fried food is a multi-billion dollar industry and most food service operations rely heavily upon frying for cooking french fries, poultry, meat, seafood, and vegetables.

The immersion frying process, also called deep fat frying, involves simultaneous heat and mass transfers. Heat convection occurs between the frying oil and the food surface and heat conduction transfers heat from the outer surface to the interior of the food product (Singh, 1995). In addition, mass transfers of moisture and oil are characterized by the migration of oil into the fried product, and the movement of water vapor from the product into the oil. Singh (1995) presented a mathematical model to describe the effect of processing conditions in deep fat frying foods and also describe heat and mass transfer phenomena in the frying process.

A variety of physical, chemical, and nutritional changes occur in food during deep fat frying. Many of these changes are functions of oil temperature, frying time and surface moisture content (Lamberg et al., 1990), product surface area (Gamble and Rice, 1988), pressure (Roa and Delaney, 1995; Mallikarjunan et al., 1995), and frying oil quality (Tseng et al., 1994). Undesirable effects could be minimized and the process could be better controlled if temperature, moisture and oil distributions in foods with respect to time could be accurately predicted. Research has been focused on different aspects of the frying operation to obtain a better understanding of the process. Many researchers have studied the relationship between oil uptake and moisture loss during frying (Roa and Delaney, 1995; Mallikarjunan et al., 1995). The considerable amount of work done on deep fat frying has been primarily focused on non-fatty foods such as french fries tortilla chips, and snack products. Research on deep fat frying of

breaded chicken parts has been limited, and most has been a result of trying to develop a new product or process.

Frying under pressure provides food products that are more juicy and tender than products fried at atmospheric pressure and the desirable characteristics of fried foods can be obtained by appropriate selection of frying temperature and pressure (Roa and Delaney, 1995; Mallikarjunan et al., 1995). The influences of parameters such as pressure, frying temperature, and frying time to produce desirable fried products are still investigated. Thus, the use of this technology is limited to a very few food products for which a method has been defined. In addition, both industrial and foodservice pressure frying equipment depends on the amount of moisture/steam released from the products to generate the required pressure. The use of this equipment is controlled by the situation where a large food load can be fried in one batch.

The primary focus of this study was to use nitrogen gas for generating the required pressure in the fryer instead of using steam released from the food. Experiments were conducted to study the effect of using nitrogen gas to supply the desired pressure on the fried chicken nuggets. The main objective of this study was to characterize the moisture retention and the reduction in oil uptake in fried foods as influenced by frying temperature, pressure, and pressure source during deep fat frying.

MATERIALS AND METHODS

Sample Preparation

Commercial breaded chicken fillets obtained from Con-Agra were used in this study. All chicken fillets were individually frozen and had the same production date. The samples were kept in a freezer (approximately -40°C) until used for the frying experiment.

Frying Experiment

Experiments were conducted using commercial vegetable oil (Bakers & Chefs, North Arkansas Wholesale Company, Inc., Bentonville, AR) as the frying medium. The product samples were allowed to equilibrate to the ambient temperature (20°C) before frying. The samples were fried at three frying temperatures (150°C, 175°C and 190°C) and three pressures (101, 163, and 184 kPa) using two pressure sources, nitrogen gas or steam released from the food, to generate the required pressure in a restaurant-type pressure fryer (model 500C, Henney Penney, Inc., Eaton, OH). The 101 kPa pressure setting denotes frying at atmospheric pressure. The pressure conditions (163 and 184 kPa) were achieved by changing the the specific dead weights and the fryer orifices in the operating valve. The pressure fryer in this research was modified by adding a nitrogen gas flow system (Innawong et al., 2001).

Another source of pressure used in this experiment was steam/moisture released from the food being fried. Pressure built-up in the fryer relied upon the amount of initial load, which was kept constant at 1200 g. A typical frying batch included 500 g of tested product and 700 g of fresh turkey breast added as the dummy load. The procedure specified that chicken fillets be cooked to doneness at the geometric center. Three different frying times were applied, namely 150 s at oil temperature 190°C, 210 s at oil temperature 175°C, and 300 s at oil temperature 150°C. A typical experiment included an average of 30 s delay in closing and opening the vessel. Every treatment was replicated three times.

Finished Product Analyses

After frying, the chicken nugget samples were air cooled for 10 min and excessive surface oil was gently removed using tissue paper. The samples were placed in freezer bags and frozen at -40°C until further analysis.

Product Moisture and Fat Content

The appropriate procedure for separating the crust and core was developed with a preliminary test. The surface layer, defined as crust, was removed after careful visual inspection. The remaining portion was considered as core. The mass of the crust and core was recorded. The moisture content of the crust and core was determined using a freeze dryer (The Virtis Company, Inc., Gardiner, NY.). Freeze drying was selected over the traditional oven drying method because the freeze dryer preserved the porous structure of the samples, which facilitated fat extraction during a subsequent fat analysis (Ateba and Mittal, 1994). The fat content of the freeze-dried samples was determined using AOAC method 960.39 (AOAC, 1995). The test was replicated three times.

Juiciness

Juiciness was measured using a press method described by Mallikarjunan and Mittal (1994). A set of filter papers (Whatman No.5, 15 cm diameter, Whatman International Ltd., Maidstone, UK.) was weighed and one gram of core was placed between two sheets of aluminum foil. This set of aluminum sheets was placed between filter papers and a set of Plexi-glass plates (15 x 15 cm). The sandwich was compressed by applying a 20 kPa pressure for 1 min. After pressing was completed, the sample along with the aluminum foils was discarded. The set of filters papers was reweighed to obtain the mass of pressed juice. The weight increase of the filter papers was correlated to the expressed juice from the product. The test was replicated three times.

Color Analysis

Color was measured using a chromameter (Model CR-300, Minolta Camera, Ltd., Osaka, Japan) calibrated to a white plate (CIE $L^* = 97.91$, $a^* = -0.68$, $b^* = 2.45$, part # 2093326) and the L^* , a^* and b^* values were used to calculate the derived color parameters. The test was replicated five times.

Breading Adhesion

The breading adhesion was calculated as described by Suderman and Cunningham (1983). Ten pieces of fried products were placed in a standard wire sieve (No. 4 US Sieve) and shaken for 1 min. The breadcrumbs that accumulated in the catch pan were weighed and the percentage of coating loss was calculated.

Texture

The texture of the fried samples was measured using a Kramer shear unit attached to a Sintech/MTS universal testing machine (model 5G, MTS, NC.). Speed of the Kramer shear unit was maintained at 100 mm/min. The peak load (N/kg), total energy (N.mm/kg) to peak load, and energy to failure point (N.mm/m³) were calculated to characterize the texture of the fried products. The test was replicated five times.

Statistical Analysis

Statistic analyses were performed using General Linear Model Program (GLM) to test the effects of frying temperature and pressure on chemical and physical characteristics of fried breaded chicken nuggets. Least Significant Difference (LSD) was used to estimate the significant differences among the means of each treatment at 5% the probability level using SAS program (SAS, 2000).

RESULTS AND DISCUSSION

In this study, the effects of frying temperature, pressure, and the pressure source (either nitrogen gas or steam) on breading adhesion were not significantly different ($P>0.05$). The loss of breading ranged between 0.23% and 0.96%.

Influence of Temperature and Pressure on Moisture

An increase in frying oil temperature resulted in a significant decrease ($P < 0.05$) in the moisture retention of chicken fillets (Table 5.1). Chicken fillets fried at oil temperatures 175°C and 190°C did not show a significant difference in moisture content in the crust and core. However, moisture content of fried products at 175°C and 190°C was significantly lower than fried products at 150°C. The moisture content of the crust at 175°C and 190°C were 25.3% and 23.6%, respectively, and the core moisture content at 175°C and 190°C were 65.7% and 64.4%, respectively (Table 5.1). The crust moisture content decreased 15.7% at 175°C and 21.2% at 190°C as compared with crust moisture at 150°C. The core moisture content decreased approximately 2.5% at 175°C and 4.4% at 190°C as compared with crust moisture at 150°C. The exterior of the chicken fillets directly contacted to hot oil caused a more rapid dehydration at higher oil temperature. This resulted in a significant increase in moisture loss. Gamble et al. (1987) proposed that during frying, the inner moisture is converted to water vapor causing a pressure gradient and escapes at the weakness point of the fried food surface.

As expected, an increase in pressure resulted in a significant increase ($P < 0.05$) in moisture retention in the crust and core (Table 5.1). Mallikarjunan et al. (1995) found that frying under pressure increased the moisture retention in the fried samples. Roa and Delaney (1995) also reported that using positive pressure during frying imparts a softer texture to the breading, while use of atmospheric pressure (101 kPa) resulted in a crispy texture. Using nitrogen gas instead of steam in pressure frying resulted in greater moisture retention in the crust and core than with the use of steam and atmospheric pressure, respectively (Table 5.1). There were no significant differences in crust and core moisture contents for frying pressures at 163 kPa and 184 kPa.

Influence of Temperature and Pressure on Juiciness

An increase in frying oil temperature resulted in no difference in juiciness in the core (Table 5.1). However, an increase in frying oil temperature tended to decrease juiciness. As expected, an increase in frying pressure resulted in a significant increase

($P < 0.05$) in juiciness (Table 5.1). In particular, frying with nitrogen gas at 184 kPa resulted in an increase in crust moisture about 19.4% compared with steam at 184 kPa, and 53.2% compared with atmospheric pressure.

Influence of Temperature and Pressure on Crust Fat Content

An increase in frying oil temperature resulted in a significant increase ($P < 0.05$) in oil uptake in the crust. However, fat content of the crust was not significantly different for frying temperatures at 175°C and 190°C. The fat content of the crust at 175°C and 190°C was 20.9% and 22%, respectively (Table 5.1). Mallikarjunan et al. (1995) also reported that higher frying temperature resulted in an increase oil uptake and surface fat content. Several researchers have reported the relationship between moisture content and oil uptake (Gamble et al., 1987; Gamble and Rice, 1988). Gamble et al. (1987) presented a linear relationship between oil uptake and water removal. In addition, the initial and final water content has a major impact on oil uptake during deep fat frying due to the replacement of moisture by oil during frying (Gamble and Rice, 1988).

As expected, an increase in pressure during frying resulted in a decrease in oil uptake. Several studies have shown that oil uptake during deep fat frying of the food products is localized at the crust (Farkas et al., 1992; Gamble et al., 1987; Keller et al., 1986). Lower pressures during frying resulted in an open network of starch and protein. This three dimensional network was porous with the voids mostly filled with air and oil (Roa and Delaney, 1995). In addition, application of pressure during frying decreased the continuity of the starch network.

Influence of Temperature and Pressure on Color of Fried Chicken Fillets

As frying oil temperature increased during frying, L^* value significantly decreased ($P < 0.05$) but a^* and b^* increased (Table 5.2). The changes in color of fried products became noticeably darker. During frying, several reactions take place including protein denaturation, starch gelatinization, and browning reaction in the batter and breading. The effect of frying pressure on crust color was significant ($P < 0.05$). An increase in pressure provided lighter fried products. The products fried under nitrogen gas

were lighter in crust color than the products fried with steam, and atmospheric pressure, respectively (Table 5.2).

Influence of Temperature and Pressure on Texture of Fried Chicken Fillets

As expected, an increase in frying oil temperature resulted in a significant increase ($P < 0.05$) in peak force, energy to peak force and total energy to failure point (Table 5.3). The texture of the products fried at higher oil temperature was harder and tougher than the products fried at lower oil temperature. The higher the oil temperature, the more the moisture loss due to an increase in the rate of heat transfer. This also confirmed by the changes in moisture content of the crust and core.

As expected, an increase in pressure resulted in significant decrease ($P < 0.05$) in peak force, energy to peak force and total energy to failure point (Table 5.3). Frying under pressure is known to produce more tender and juicy fried products (Roa and Delaney, 1995; Mallikarjunan et al., 1995). In addition, Roa and Delaney (1995) found that using positive pressure during frying imparted a softer texture to the breading, while use of atmospheric pressure resulted in a crispy texture. Lower pressures during frying represented more open starch-protein network, more crust porosity, and more continuity of the starch granules (Roa and Delaney, 1995). Thus, the fried products had less moisture in the crust and were brittle and fluffy in texture. These caused more force and energy needed to shear the products.

The effect of the pressure source on peak force, energy to peak force and total energy to failure point was significant ($P < 0.05$). Frying with nitrogen gas resulted in significantly lower ($P < 0.05$) energy to peak force and total energy to failure point than frying with steam and atmospheric pressure, respectively (Table 5.3). This result indicated that the products fried with nitrogen had more crust and core moisture, softer crust, and were more tender and juicy than products fried with steam and atmospheric pressure.

CONCLUSIONS

Frying temperature, pressure, and pressure source directly affected fried chicken fillet quality. An increase in pressure provided more moisture retention and juiciness in the core than frying with steam and atmospheric frying, respectively ($P < 0.05$). Chicken fillets fried with nitrogen gas were more juicy and tender than fillets fried with steam because frying with nitrogen gas increased the moisture retention and pressed juice of the fried product ($P < 0.05$). Frying with nitrogen gas also produced the fried product that had significantly lower peak force, energy to peak force, and total energy to failure point ($P < 0.05$) than frying by steam. An increase in the oil temperature resulted in an increase in the moisture loss, oil uptake in crust, and the texture of fried fillets were tougher and harder ($P < 0.05$).

REFERENCES

- AOAC. 1995. Official Methods of Analysis of AOAC International. 16th edition, vol. 2, Arlington, Virginia.
- Ateba, P. and Mittal, G.S. 1994. Modeling the deep-fat frying of beef meatballs. Intl. J. Food Sci. Technol. 29: 429-440.
- Farkas, B.E., Singh, R.P., and McCarthy, M.J. 1992. Determination of oil/water distribution within fried foods. Presented at the Annual Meeting of the Inst. of Food Technologists, New Orleans, LA.
- Gamble, M.H. and Rice. P. 1988. The effect of slice thickness on potato crisp yield and composition. J. Food Eng. 8: 31-46.
- Gamble, M.H., Rice, P., and Selman, J.D. 1987. Relationship between oil uptake and moisture loss during frying potato slices from c.v. Record U.K. Tubers. Intern. J. Food Sci. and Techn. 22: 233-241.
- Innawong, B., Mallikarjunan, P., and Cundiff, J.S. 2001. The effect of pressure conditions on quality of chicken nuggets fried with constant frying time. (In Preparation).
- Keller, Ch., Escher, F., and Solms, J.A. 1986. Method for localizing fat distribution in deep-fried potato products. Lebensm- Wiss. U. Technol. 19(4): 346-348.
- Lamberg, I., Hallstrom, B. and Olsson, H. 1990. Fat uptake in a potato drying/frying process. Lebensm-Wiss. U. Technol. 23: 295-300.
- Mallikarjunan, P. and Mittal, G.S. 1994. Meat quality kinetics during beef carcass chilling. J. Food Sci. 59: 291-294, 302.
- Mallikarjunan, P., Chinnan, M.S. and Balasubramaniam, V.M. 1995. Mass transfer in edible film coated chicken nugget: influence of frying temperature and pressure. CoFE. 107-111.
- Orthoefer, F.T. and Cooper, D.S. 1996. Evaluation of used frying oil. Ch. 16 in "*Deep frying. Chemistry, nutrition, and practical applications*". E.G. Perkins and M.D. Erickson (Ed.), p. 285-296. AOCS Press, Champaign, IL.
- Roa, V.N.M. and Delaney, A.M. 1995. An engineering perspective on deep-fat frying of breaded chicken pieces. Food Technol. 49(4): 138-141.

- Saguy, I.S. and Pinthus, E.J. 1995. Oil uptake during deep-fat frying: Factors and mechanism. *Food Technol.* 49(4): 142-145, 152.
- SAS Institute, 2000. SAS Institute Inc., Cary, NC.
- Singh, R.P. 1995. Heat and mass transfer in foods during Deep-fat frying. *Food Technol.* 49(4): 134-137.
- Suderman and Cunningham, 1983. *Batter and Breading*. AVI Pub. Co., Westport, CT. 224p.
- Tseng, Y.C., Moreira, R.G., and Sun, X. 1994. Physical and chemical properties of oil degradation related to food quality in deep-fat frying. Paper No. 94-6524. Presented at 1994 International Winter Meeting of ASAE, Atlanta, GA. Dec 13-16.
- Varela, G. 1988. Current facts about the frying of food. Ch. 1 in "*Frying of food*", p. 9-25. G. Varela, A.E. Bender and I.D. Morton (Ed.), Ellis Horwood Ltd., Chichester, England.

Table 5.1 Mean moisture content, crust fat content, and juiciness for different frying parameters.

Effect of temperature

Temperature (°C)	Moisture ¹ (%)		Crust Fat ¹ (%)	Juiciness ¹ (%)
	Crust	Core		
150	30.00 ^a	67.36 ^a	18.73 ^a	17.21 ^a
175	25.29 ^b	65.69 ^b	20.94 ^b	16.60 ^a
190	23.64 ^b	64.38 ^b	22.00 ^b	16.32 ^a

Effect of pressure

Source of pressure	Pressure (kPa)	Moisture ² (%)		Crust Fat ² (%)	Juiciness ² (%)
		Crust	Core		
atmosphere	101	21.39 ^a	63.66 ^a	21.44 ^a	12.79 ^a
steam	163	24.59 ^{ab}	65.09 ^b	20.53 ^b	15.51 ^b
steam	184	26.97 ^{bc}	65.38 ^b	20.37 ^b	16.42 ^b
nitrogen	163	28.69 ^c	67.16 ^c	20.42 ^b	19.23 ^c
nitrogen	184	29.91 ^c	67.75 ^c	20.02 ^c	19.60 ^c

¹ n = 45

² n = 27

^{abc} means within a column with unlike superscript letters are significantly different (P<0.05).

Table 5.2 Mean crust color and core color for different frying parameters.

Effect of temperature

Temperature (°C)	Crust ¹			Core ¹		
	L*	a*	b*	L*	a*	b*
150	52.59 ^a	4.70 ^a	29.09 ^a	76.88 ^a	0.23 ^a	13.22 ^a
175	45.56 ^b	9.50 ^b	33.83 ^b	75.09 ^b	0.37 ^a	13.76 ^b
190	39.72 ^c	13.61 ^c	32.77 ^b	72.65 ^c	0.30 ^a	15.36 ^b

Effect of pressure

Source of pressure	Pressure (kPa)	Crust ²			Core ²		
		L*	a*	b*	L*	a*	b*
atmosphere	101	43.81 ^a	11.00 ^a	33.77 ^a	73.34 ^a	0.21 ^a	13.79 ^a
steam	163	44.92 ^a	9.66 ^b	32.75 ^a	75.01 ^b	0.06 ^a	14.16 ^a
steam	184	44.29 ^a	9.21 ^b	31.28 ^b	73.19 ^a	0.01 ^a	14.36 ^a
nitrogen	163	48.66 ^b	9.01 ^b	31.60 ^b	76.71 ^{bc}	0.45 ^b	13.67 ^a
nitrogen	184	48.11 ^b	7.47 ^c	30.09 ^c	76.11 ^c	0.75 ^b	14.60 ^a

¹ n = 75

² n = 45

^{abc} means within a column with unlike superscript letters are significantly different

(P<0.05).

Table 5.3 Mean peak force, energy to peak force, and total energy to failure point for different frying parameters.

Effect of temperature

Temperature (°C)	Peak force ¹ x 10 ³ (N/kg)	Energy to peak force ¹ x 10 ³ (N.mm/kg)	Total energy to failure point ¹ x 10 ⁶ (N.mm/m ³)
150	32.90 ^a	144.05 ^a	24.68 ^a
175	45.38 ^b	194.45 ^b	33.07 ^b
190	53.52 ^c	213.88 ^c	36.37 ^c

b-Pressure

Source of Pressure	Pressure (kPa)	Peak force ² x 10 ³ (N/kg)	Energy to peak force ² x 10 ³ (N.mm/kg)	Total energy to failure point ² x 10 ⁶ (N.mm/m ³)
atmosphere	101	51.32 ^a	224.56 ^a	43.60 ^a
steam	163	44.44 ^b	183.25 ^b	31.08 ^b
steam	184	46.21 ^b	182.81 ^b	30.04 ^b
nitrogen	163	38.01 ^c	162.56 ^c	26.43 ^c
nitrogen	184	39.68 ^c	167.48 ^c	25.73 ^c

¹ n = 75

² n = 45

^{abc} means within a column with unlike superscript letters are significantly different (P<0.05).

CHAPTER 6

The Determination of Frying Oil Quality Using A Chemosensory System

ABSTRACT

The application of chemosensory systems to evaluate volatile compounds is currently being introduced in the food industries for quality control, process monitoring, and odor quality evaluation. This study was conducted to determine the possibility of using a chemosensory system to differentiate among varying intensities of oil rancidity and investigate discrimination between good, marginal and unacceptable frying oils. Fresh, 1-day, 2-day used and discarded frying oils were obtained from a fast food restaurant in each frying cycle for 4 weeks. The oil samples were kept at 4°C and analyzed using a chemosensory system. The discrimination between good, marginal and unacceptable frying oils with regard to rancidity was examined and the results were compared to their physical and chemical properties such as dielectric constant, peroxide value (PV), and free fatty acid content (FFA). The different qualities of frying oils were successfully evaluated using the chemosensory system. Good discrimination and stability were obtained for identification between acceptable and unacceptable qualities of frying oil. Good correlation (r) from 0.87 to 0.96 was found between changes in physical and chemical properties of abused oils and the sensor signals. Because of its reliability, convenience, and speed, the chemosensory system is an alternative for the fried food industry to monitor and control oil quality in the frying process.

Keywords: chemosensory system, electronic nose, frying oil quality, dielectric constant, free fatty acid content, peroxide value

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INTRODUCTION

The quality of frying oil used in deep fat frying contributes to the quality of the fried food. The quality of the frying medium and of the food fried in that oil are intimately related (Blumenthal, 1991). It is known that frying oils used continuously or repeatedly at high temperatures in the presence of oxygen and water from the food being fried, are subject to thermal oxidation, polymerization, and hydrolysis, and the resultant decomposition products adversely affect flavor and color (Clark and Serbia, 1991; Tyagi and Vasishtha, 1996; White, 1991). In addition, undesirable constituents produced from degraded frying oils may even be harmful to health. Several factors influence the quality of frying medium including air exposure, stability of the oil to oxidation, steam/moisture exposure, contamination of frying oil with fat from the food being fried, and contamination from charred food particles primarily from the breading mixes used to coat fried foods (Orthoefer, 1988).

Deterioration of frying oils is generally followed by changes in free fatty acid level, color of the used oil, or an increase in polarity of the oil (Melthon et al., 1994; Orthoefer, 1988; Orthoefer et al., 1996; Paradis and Nawar, 1981; Tan et al., 1985; White, 1991). Various criteria are being used to judge when the frying oils needs to be discarded. In restaurants and food services, changes in physical properties of frying oils have been used as an indicator of oil quality (Moreira et al., 1999). For example, the frying oil may be discarded when the oil becomes dark, too much smoke, strong odor, greased texture, or when a persistent foam layer of specified thickness is observed (Moreira et al., 1999). However, before an operator sees such effects, the oil has usually suffered considerable decomposition. In the food industry, not only physical tests but chemical tests are also used to measure oil quality including acidity, polymer content and/or total polar content (Moreira et al., 1999; White, 1991).

Previous monitoring methods used to analyze the volatile compounds and aroma in food needed either a highly trained sensory panel or GC/MS techniques (Hodgins and Simmonds, 1995; Hodgins, 1996; Mielle and Marquis, 1998; Yang et al., 2000). Each technique has its limitations. The sensory evaluation is time consuming and expensive due to dependence on the training of the judges and the description method used. The

results from GC/MS still are difficult to match and directly relate to the quality of the food (Hodgins, 1996; Yang et al., 2000). Thus, there has been a genuine need for a quick, simple, and powerful objective test for indicating deterioration of oil.

Recently, there exists an interest in using arrays of different chemical sensors for identification of volatile compounds and different odors in food products (Lacey and Osborn, 1998; Philip et al., 1997; Schaller and Bosset, 1998; Warburton, 1996). Chemosensory system, also called an “electronic nose”, consists of a series of sensors that respond to the volatile components in the head space above a tested sample. The response is used for identification and discrimination between samples (Hodgins and Simmonds, 1995; Hodgins, 1996; Mielle, 1996; Payne, 1998). Pattern recognition routines based on either statistical methods or on artificial neural networks are the powerful keys to evaluate the responses of sensor arrays (Hodgins and Simmonds, 1995). Most commercially used sensors include metal oxide semiconductors (MOS), conducting polymers (CP), bulk acoustic wave (BAW), surface acoustic wave (SAW) and quartz micro-balance (QMB) sensors (Hodgins, 1996; Mielle, 1996; Philip et al., 1997). Presently, commercial chemosensory systems have become more readily available in the market. Chemosensory systems are currently introduced in the food industries for effective and convenient quality control, process monitoring for cooking and fermentation processes, evaluation of the maturation and ripening of wine, cheese, and meat products, and odor quality evaluation for food packaging (Mielle, 1996). Interest exists in using a chemosensory system to investigate odor and volatile compounds in edible oil (Aparicio et al., 2000; Muhl et al., 2000; Yang, 2000).

The study was conducted to determine the feasibility for use of a chemosensory system to differentiate among varying intensities of oil rancidity and investigate discrimination between good, marginal, and unacceptable frying oils.

MATERIALS AND METHODS

Sample Preparation

Peanut oil samples were received from a local fast food restaurant in each frying cycle for 4 weeks. In addition, all oil samples were collected from the fryer used to fry only poultry products. The oil samples were classified into four categories consisting of fresh, 1-day, 2-day used, and discarded oils (Fig. 6.1). All oil samples were kept at 4°C until analyzed using a chemosensory system or chemical methods used to measure the intensity of oil rancidity.

Measuring Quality of Oil

The discrimination among each frying oil sample with respect to rancidity was examined using a chemosensory system. All results were compared to their physical and chemical analyses including dielectric properties, free fatty acid content (FFA), and peroxide value (PV). Percentage of free fatty acid was determined by alkaline titration according to AOCS method Ca 5a-40 (AOCS, 1989) and results were expressed as oleic acid percentage. Peroxide value was determined by AOAC method 965.33 (AOAC, 1995). Each measurement was replicated three times.

Food Oil Sensor

Changes in dielectric properties of frying oil were measured using Food Oil Sensor (model NI-20, Northern Technologies Intl. Corp., Lino Lakes, MN) (Fig. 6.2). This instrument operates at frequency of 5 MHz. Changes in the electric flux density for a given electric field intensity caused by used frying oil are attributed to the dielectric constant changes of the fried oil (Graziano, 1979).

The test consists of two steps. In first step, the instrument was balanced to a zero state with a “standard” (unused, fresh sample of the same frying oil to be tested). A few drops of the fresh oil or test oil were placed in an open test cell, which has a heater and

temperature controller. Since the dielectric properties vary with the oil temperature, it is essential that all readings must be taken at the same temperature. The unit will not permit a test to be performed until the sample has reached 79°C (Graziano, 1979). After calibration using fresh oil, the oil was then removed from the instrument cup with tissue paper, then samples were next placed in the cup and measurements were taken. Each measurement was replicated three times.

Off-Flavor

In this study, the possibility of using a chemosensory system (or electronic nose) to discriminate between various intensities of oil rancidity was explored. The chemosensory system (model QMB-6, Perkin Elmer, Norwalk, CT) was connected to a HS40-XL auto sampler and consisted of six different sensors differing in polarity (Fig. 6.3). Sensor substrate of this instrument is a quartz-microbalance based sensor (bulk acoustic wave gas sensor). A change in mass of a chemical compound causes a change in frequency as indicated by each sensor. The sensibility in this type of sensor is 1.2 Hz/ng. For interpretation of signal sensor data, QMBSOFT-NT software was used to analyze the data.

An oil sample of 1.5 ml was placed into a 22-ml glass vial. Using a crimping tool, each sample vial was sealed with a fitted cap and septum (PTFE-coated butyl rubber septa or PTFE-coated silicone rubber septa). Each vial was sealed tightly to prevent leaks and an uncharacteristic decrease in sensor signal. Then, the sample vials were placed in the instrumental tray for further analysis. In this study, three sensor cell temperature (25°C, 35°C and 45°C), two different sample temperature (80°C and 100 °C), and HS-needle temperature (100°C) were set to perform the frying oil test. The following time scheme, thermostat (60 min), zero level (30 s), pressurization (90 s), building-up (150 s), signal level (30 s), and purge (30 min) was used as a time interval setting. These time intervals were selected based on the recommendation by the equipment manufacturer.

Statistical Analysis

Data were subjected to analysis of variance using General Linear Model (GLM) and Least Significant Difference test (LSD) at 5% confidence level was performed to determine the differences among means using SAS procedures (SAS, 2000). Data collected from chemosensory system were analyzed using Discriminant Function Analysis (DFA) from QMBSOFT-NT software to differentiate the quality of frying oil with regard to the responses of all sensors.

RESULTS AND DISCUSSION

Oil Quality Detected Using Chemical Methods

In this present study, as expected, all quality attributes (dielectric constant, peroxide value and free fatty acid content) of peanut oil samples obtained from fried chicken process significantly increased ($P < 0.05$) with frying time (Fig. 6.4). The dielectric constant of the discarded oil increased up to 73%. Normally, frying oils undergo extensive degradation and complex chemical transformations when heated. The presence of air and water introduced as steam during the frying process can accelerate the deterioration of frying oil (Clark and Serbia, 1991). As oil thermally and oxidatively breaks down, there is an increase in the number of polar molecules, which directly increases the dielectric constant (Fritsch et al., 1979; Graziano, 1979; White, 1991).

During frying, oils are hydrolyzed to form free fatty acids and mono- and diglycerides and these compounds accumulate in the frying oil with repeated use. In addition, oils also oxidize to form hydroperoxide, conjugated dienoic acids, epoxides, hydroxides, aldehydes, and ketones. These compounds may undergo fission into smaller fragments or may remain in the triglyceride molecule and cross-link with each other, leading to dimeric and higher polymeric triglycerides. An increase in volatile compounds resulted in an increase in free fatty acid content and peroxide value in the oil samples (Fig. 6.4).

Measuring Oil Quality Using a Chemosensory System

Each type of oil samples, fresh, 1-day, 2-day old, and discarded oils showed very similar sensor responses, and the overall signal pattern appeared similar to each other. However, the signal height, which indicated the presence of a dominant headspace compound, was the biggest observed difference in each sensor. These could be seen as an indicator that the signal response of each type of oils received from the same sensor was principally caused by the same chemical compounds. The discarded oil got the highest overall signal response and the overall signal responses for 2-day, 1-day old oil were lower, respectively. As expected, the overall signal response for the fresh oil was the lowest (Fig. 6.5). Since all six sensors responding to the fresh oil sample showed very low signal heights, it could be correlated to very low concentration of the compounds in the headspace compared to other types of oil. It is known that the rancidity of edible oils is correlated to some volatile rancidity markers, which usually dominate and are detectable in the headspace. Thus, samples that were described as acceptable showed lower signals than unacceptable samples. Together with the observation of the similar patterns, it seemed that the quality of frying oils could be easily classified simply using a chemosensory system. In particular, it successfully discriminated the signal responses between the discarded oil and fresh oil.

The reduction in sensor cell temperature from 45°C to 25°C increased the discrimination and differentiation of each sensor response among fresh, 1-day, 2-day old oils (Fig. 6.5). In addition, each sensor response provided all positive values at sensor cell temperature of 25°C. Thus, sensor cell temperature of 25°C was selected for future experiments due to its ability to differentiate oil quality better than other temperatures.

Decreasing sample temperature resulted in lower signal response for all oil samples (Fig. 6.6). This was primarily due to the release of less volatiles compounds from the hot oil at lower sample temperature. However, decreasing the sample temperature from 100°C to 80°C resulted in better discrimination among fresh, 1-day, and 2-day old oils (Fig. 6.6). Similar to the results from the signal responses, the discriminant function analysis (DFA) plot of fresh, 1-day, and 2-day old oils overlapped each other at sample temperature of 100°C. This overlap could be the result of adding fresh oil in the

fryer every three hours to maintain the oil level. However, the best discrimination among three types of oils was found at sample temperature of 80°C (Fig. 6.7).

Changes in oil quality due to its degradation resulted in an increase in sensor response for sensors 1, 3, 4, and 6. Sensor no. 3 showed the highest sensitivity to detect the dominant chemical compounds in the headspace of tested vials as evidenced by the highest signal height. The sensitivity of sensors no. 4, 1, and 6 with respect to the same dominant chemical substances decreased, respectively. Good correlation (r) from 0.87 to 0.96 was found between changes in physical and chemical properties of abused oils and sensor signals (Fig. 6.8). Thus, it can be easy to evaluate these physical and chemical changes from chemosensory sensor results.

Further research must be investigated to more effectively utilize this equipment as a powerful tool in quality and process control in the frying industry. To ensure the reliability of new applications, the chemosensory system should be verified by an external method such as GC.

CONCLUSION

QMB-6 chemosensory system is another optional method for measuring the oil rancidity. According to the results of extensive differences in signal responses for all six sensors and the visual graphic plots using discriminant analysis technique, various oil qualities can be effectively and successfully discriminated and identified from each other. A value of 80°C for sample temperature and sensor cell temperature at 25°C resulted in a better discrimination among fresh, 1-day, 2-day old oils. Good correlation was found between chemical properties of oil samples and sensor signals from the QMB-6 chemosensory system.

REFERENCES

- AOAC. 1995. Official Methods of Analysis of AOAC International. 16th edition, vol. 2, Arlington, Virginia.
- AOCS. 1989. Official Methods and Recommended Practices of the American Oil Chemists' Society. 4th edition, Champaign, IL.
- Aparicio, R., Rocha, S.M., Delgadillo, I. and Morales, M.T. 2000. Detection of rancid defect in virgin olive oil by the electronic nose. *J. Agric. Food Chem.* 48: 853-860.
- Bazzo, S., Loubet, F. and Tan, T.T. 1998. Quality control of edible oil using an electronic nose. *Seminars in Food Analysis.* 3(1): 15-25.
- Blumenthal, M.M. 1991. A new look at the chemistry and physics of deep fat frying. *Food Technol.* 45(2): 68-72, 94.
- Clark, W.L. and Serbia, G.W. 1991. Safety aspects of frying fats and oils. *Food Technol.* 45(2): 84-89, 94.
- Fritsch, C.W., Eggerg, D.C. and Magnuson, J.S. 1979. Changes in dielectric constant as a measure of frying oil deterioration. *J. Am. Oil Chemists' Soc.* 56(8): 746-750.
- Graziano, V.J. 1979. Portable instrument rapidly measures quality of frying fat in food service operations. *Food Technol.* 33(9): 50-57.
- Lacey, R.E. and Osborn, G. S. 1998. Application of electronic noses in measuring biological systems. Paper No. 986116. ASAE meeting presentation. P. 1-17.
- Hodgins, D. and Simmonds, D. 1995. Sensory technology for flavor analysis. *Cereal Foods World.* 40(4): 186-191.
- Hodgins D. 1996. Electronic nose technology. *Perfumer & Flavorist.* 21(3): 45-46, 48.
- Melton, S.L., Jafar, S., Sykes, D. and Trigiano, M.K. 1994. Review of stability measurements for frying oils and fried food flavor. *J. Am. Oil Chemists' Soc.* 71(12): 1301-1308.
- Mielle, P. and Marquis, F. 1998. 'Electronic nose': Improvement of the reliability of the product database by using new dimensions. *Seminars in Food Analysis.* 3(1): 93-105.

- Mielle, P. 1996. 'Electronic noses': Towards the objective instrumental characterization of food aroma. *Trends in foods science and technology*. 7(12): 432-438.
- Moreira, R.G., Elena Castell-Perez, M. and Barrufet, M.A. 1999. Frying oil characteristics. Ch. 3 in "*Deep-fat frying. Fundamentals and applications*". Aspen Publishers, Inc., Gaithersburg, ML. p. 33-74.
- Muhl, M., Demisch, H.U., Becker, F. and Kohl, C.D. 2000. Electronic nose for detecting the deterioration of frying fat-Comparative studies for a new quick test. *Eur. J. Lipid Sci. Technol.* 102: 581-585.
- Orthofer, F.T. 1988. Care of food service frying oils. *J. Am. Oil Chemists' Soc.* 65(9): 1417-1419.
- Orthofer, F.T., Gurkin, S. and Liu, K. 1996. Dynamic of frying. Ch. 11 in "*Deep frying. Chemistry, nutrition, and practical applications*". E. G. Perkins and M. D. Erickson (Ed.), p. 223-244. AOCS Press, Champaign, IL.
- Paradis, A. J. and Nawar, W.W. 1981. Evaluation of new methods for the assessment of used frying oils. *J. Food Sci.* 46: 449-451.
- Payne, J.S. 1998. Feature electronic nose technology. An overview of current technology and commercial availability. *Food science & Technology Today*. 12(4): 196-200.
- Philip, N., Bartlett, M.E. and Gardner, J.W. 1997. Electronic noses and their application in the food industry. *Food Technol.* 51(12): 44-48.
- SAS. 2000. *SAS User's Guide: Statistics*, Version 8 edition. SAS Institute Inc., Cary, NC, USA.
- Schaller, E. and Bosset, J.O. and Escher, F. 1998. 'Electronic noses' and their applications in the food industry: A review. *Seminars in Food Analysis*. 3(1): 119-124.
- Tan, Y.A., Ong, S.H., Berger, K.G., Onn, H.H. and Poh, B.L. 1985. A study of the cause of rapid color development heated refined palm oil. *J. Am. Oil Chemists' Soc.* 62(6): 999-1006.
- Tyagi, V.K. and Vasishta, A.K. 1996. Changes in the characteristics and composition of oils during deep-fat frying. *J. Am. Oil Chemists' Soc.* 73(4): 499-506.
- Warburton, J. 1996. The electronic 'nose'-the technology and applications. *Food science & Technology Today*. 10(2): 91-93.

White, P.J. 1991. Methods for measuring changes in deep-fat frying oils. *Food Technol.* 45(2): 75-80.

Yang, M.Y., Han, K.Y. and Noh, B.S. 2000. Analysis of lipid oxidation of soybean oil using the portable electronic nose. *Food Sci. Biotechnol.* 9(3): 146-150.

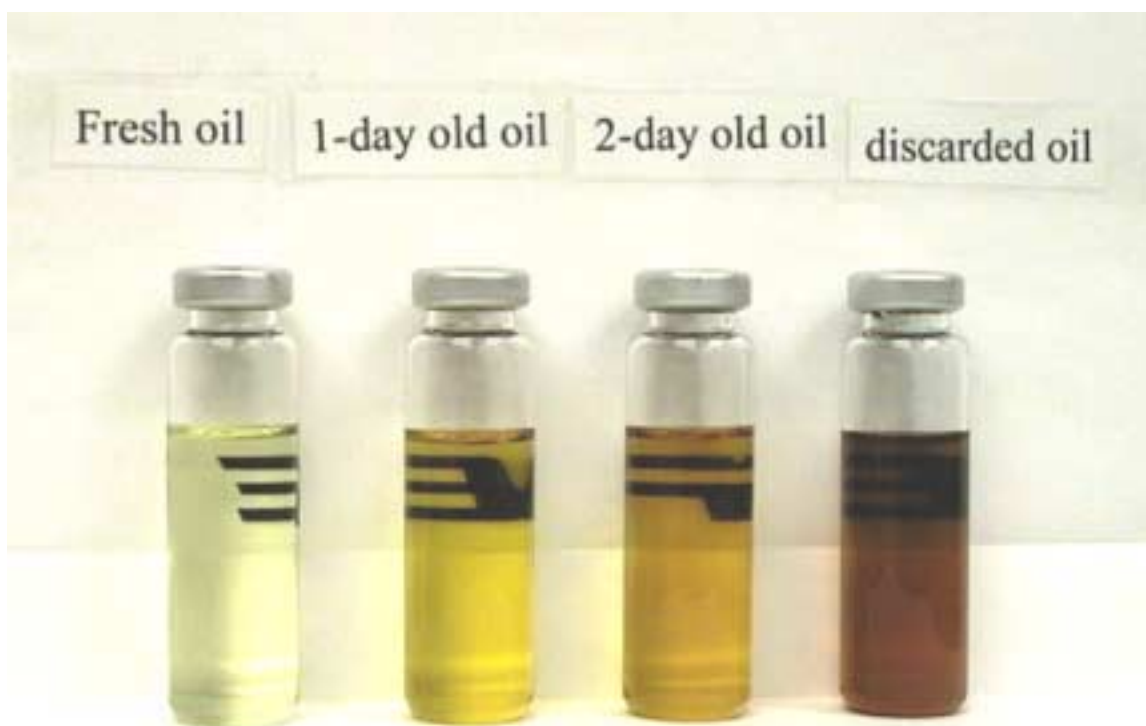


Figure 6.1 Peanut oils collected from fried chicken restaurant.



Figure 6.2 FoodOil Sensor model NI-20 for measuring dielectric constant.



Figure 6.3 Chemosensory system model QMB-6 connected to HS40 XL auto sampler.

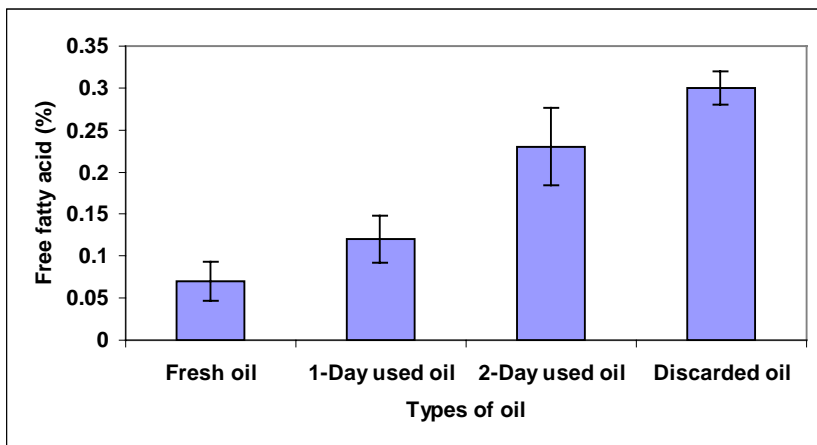
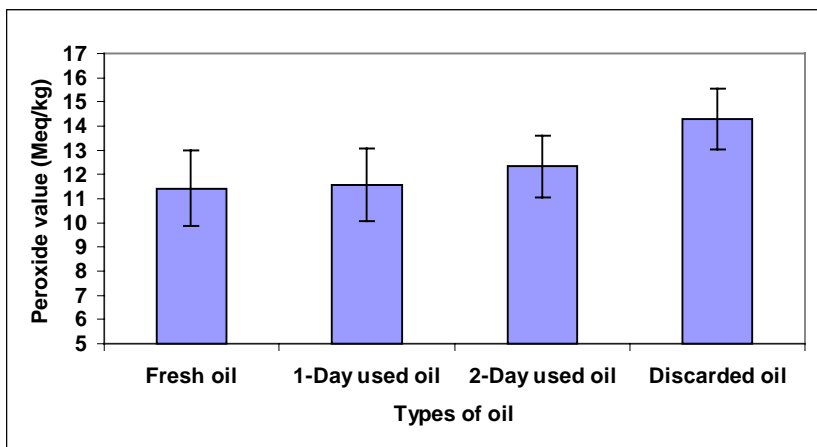
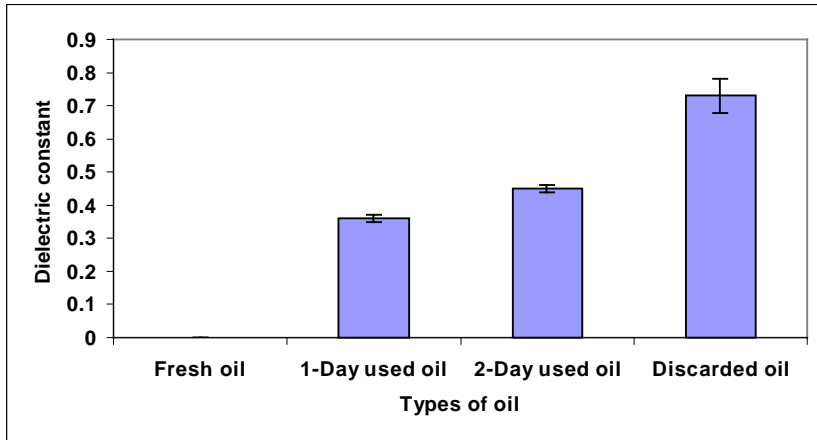


Figure 6.4 Quality attributes of oil samples from fried chicken restaurant.

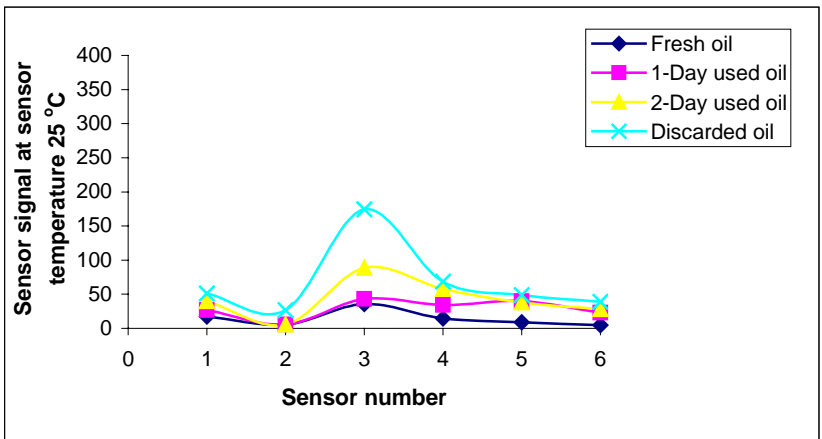
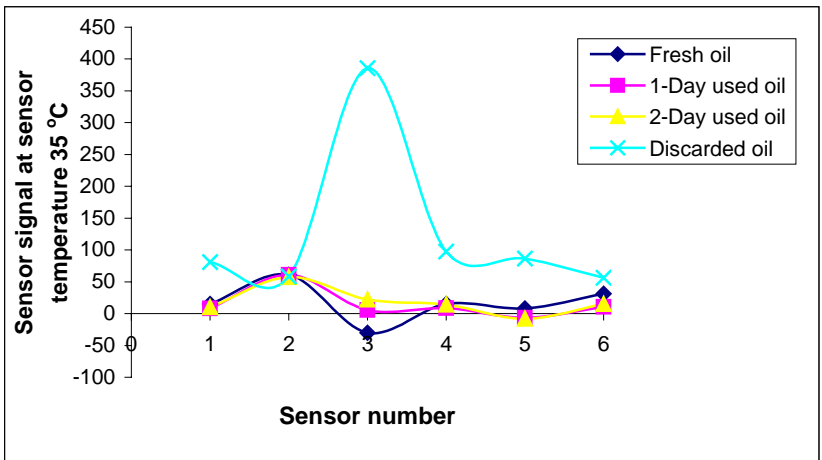
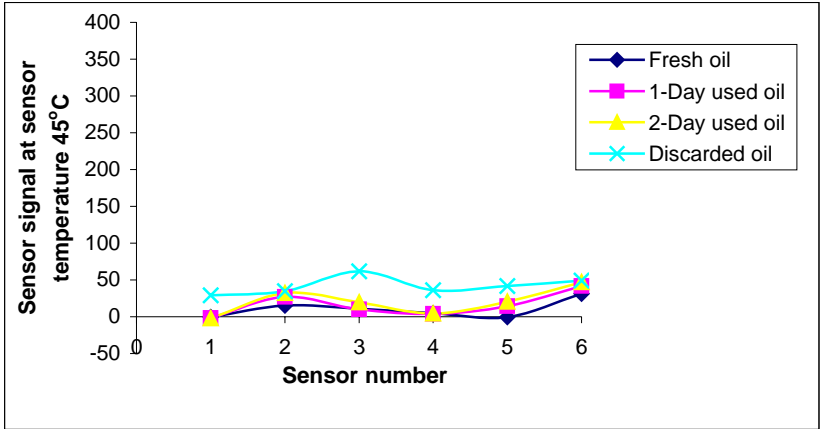


Figure 6.5 Sensor responses to different oil samples using sample temperature 100°C and three different sensor cell temperatures (25°C, 35°C, and 45°C).

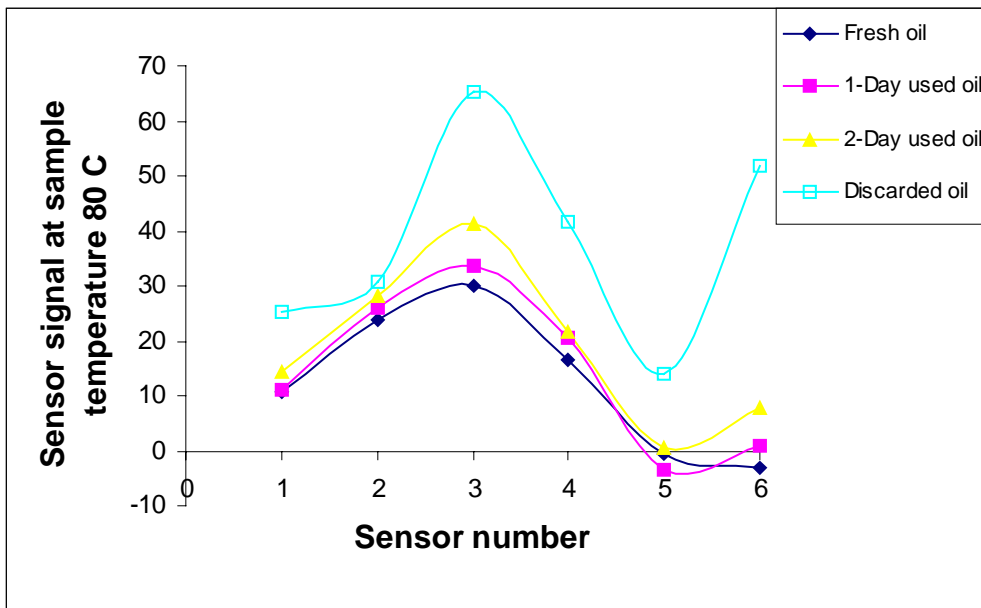
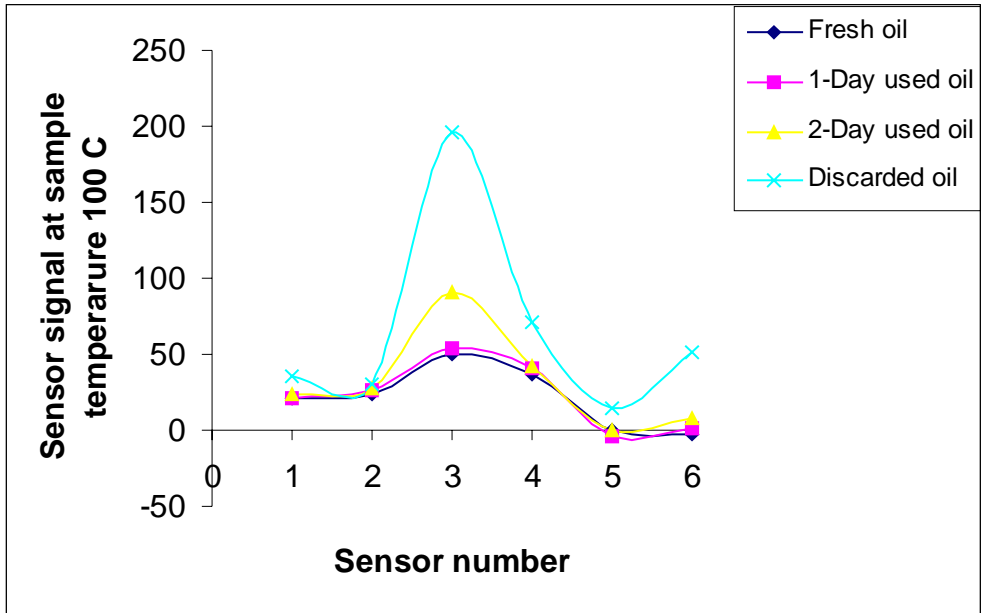


Figure 6.6 Signal responses to all oil samples using different sample temperatures (100°C and 80°C) but the same sensor cell temperature 25°C.

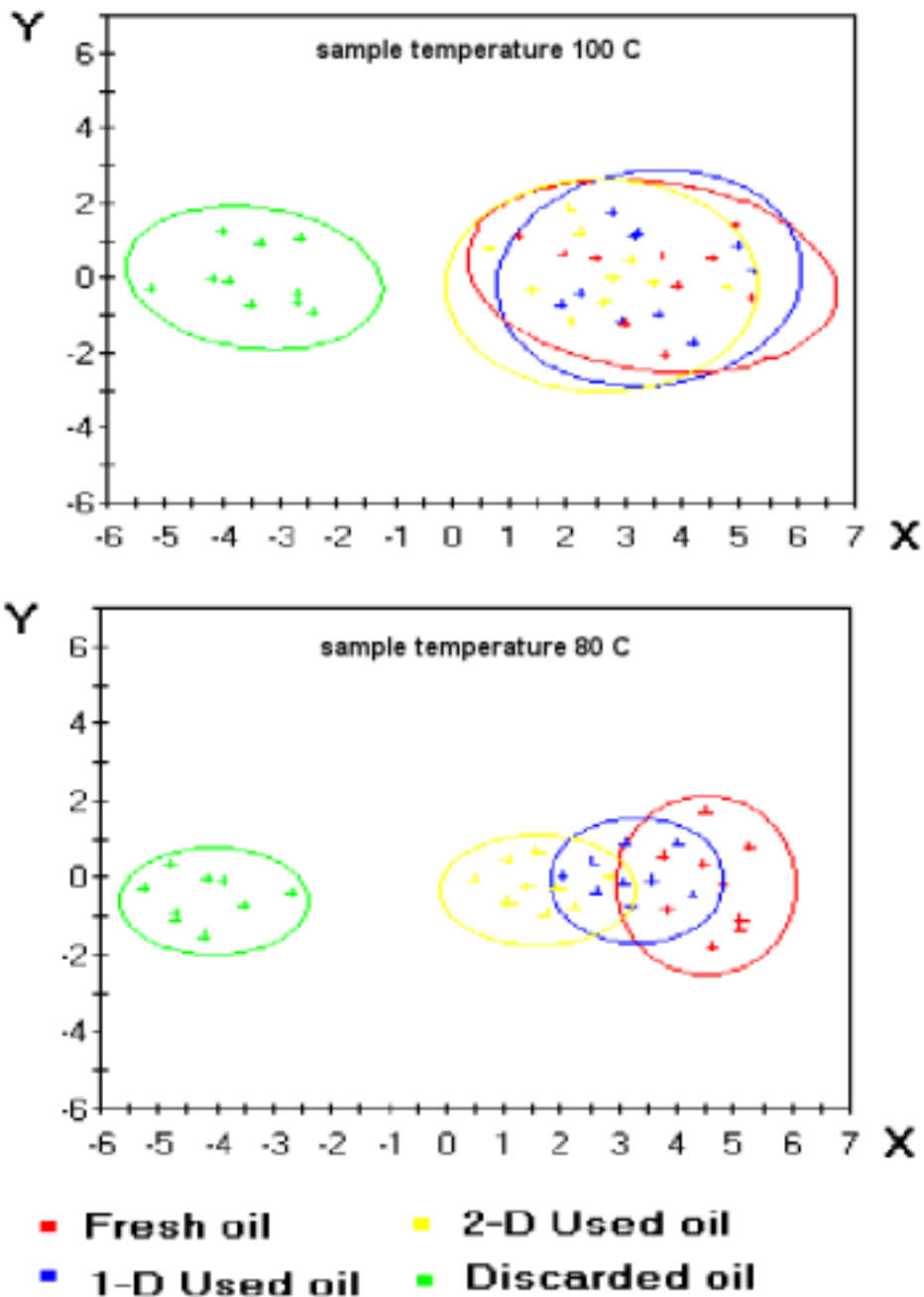


Figure 6.7 Graphic feature space plot for all oil samples using two different sample temperatures (100°C and 80°C) and sensor cell temperature 25°C.

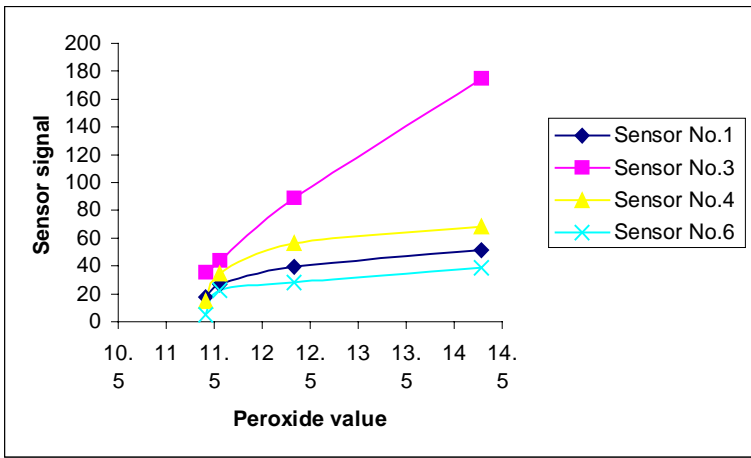
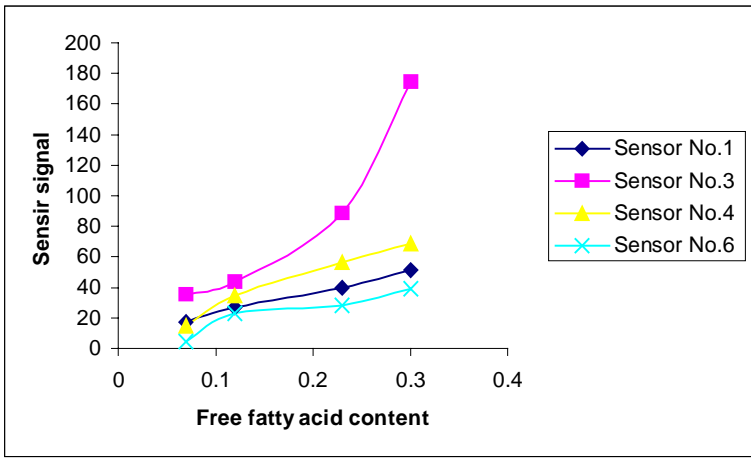
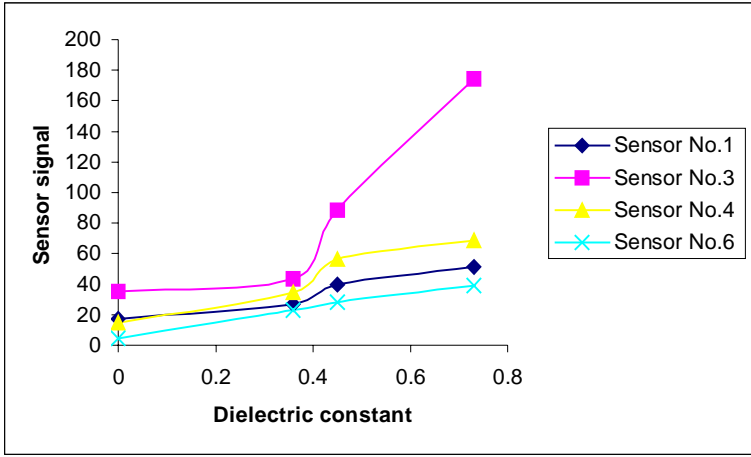


Figure 6.8 Correlation between quality attributes of oils and signal sensor obtained from various sensor number.

CHAPTER 7

The Determination of Frying Oil Quality Using Fourier Transform Infrared Attenuated Total Reflectance

ABSTRACT

The possibility of using the whole spectra (wavenumbers between 4000 and 850 cm^{-1}) from Fourier transform infrared attenuated total reflectance spectroscopy (FTIR-ATR) to differentiate between good, marginal and unacceptable oils with regard to various intensities of oil rancidity was investigated. Fresh, used, and discarded oils were collected from several fast food restaurants from each frying cycle for 4 weeks. These samples were kept at 4°C and then analyzed using FTIR-ATR. The deterioration of the oil over time was successfully quantified using chemical and physical parameters and FTIR-ATR. Dielectric constant, peroxide value, free fatty acid content, and density of oils significantly ($P < 0.01$) increased with frying time. The FTIR data correlated very well with chemical measurements. The correlation (r) between FTIR absorbance at 3300 cm^{-1} and free fatty acid content was from 0.84 to 0.94 for oils from the three restaurants. Similarly, the correlation (r) between FTIR absorbance at 3471 cm^{-1} and peroxide value was from 0.90 to 0.97 for oils from the same three restaurants. In conjunction with principal component analysis technique (PCA), the results of PCA plots using the whole spectra (4000 to 850 cm^{-1}) showed good discrimination and stability for identification between acceptable and unacceptable frying oils with regard to rancidity. The PCA plot also showed the marginal oil quality from the good quality to the unacceptable quality.

Keywords: FTIR-ATR, frying oil quality, dielectric constant, free fatty acid content, peroxide value

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INTRODUCTION

Deep fat frying is a popular food preparation technique because it is fast and convenient. The quality of the frying oil and the quality of the food fried in that oil are intimately related (Blumenthal, 1991). Repeated use of frying oil produces undesirable constituents that may pose health hazards.

Lipid oxidation, one of the important deterioration reactions affecting edible fats and oils, is initiated by various factors including light, elevated temperatures, oxygen, and water from the food being fried. During frying, the oils are subjected to thermal oxidation, polymerization, and hydrolysis, and the resultant decomposition products adversely affect flavor and color (Clark and Serbia, 1991; Tyagi and Vasishtha, 1996; White, 1991).

Deterioration of frying oils generally is followed by changes in free fatty acid level, color of the used oil, or an increase in polarity of the oil (Melton et al., 1994; Orthoefer, 1988; Orthoefer et al., 1996; Paradis and Nawar, 1981; Tan et al., 1985; White, 1991). Thus, various criteria are used to judge when the frying oils need to be discarded. Traditional chemical methods of oil analysis are commonly time consuming, and/or need substantial amounts of solvents. The development of a simple and rapid test is needed in order to capably monitor oil quality.

Fourier transform infrared (FTIR) represents an important tool used for quality control and monitoring process in the food industry because it is less expensive, better in performance and easier to use than other methods (Van de Voort et al., 1993). FTIR has been used for quantitative and qualitative measurements of edible oils and fats as the results of the development of instrumental macro-programming for automated routine operations and the application of chemometrical techniques for multicomponent analysis (Goburdhun et al., 2001, Van de Voort et al., 1994, Yang and Irudayaraj, 2000). FTIR has been used to determine *cis* and *trans* content, iodine value, saponification number, peroxide value, anisidine value, free fatty acid content of oil and fat samples, and food compositions (Dubois et al., 1996, Ma et al., 1997, Van de Voort et al., 1993, Van de Voort et al., 1994). Limited research work has been performed on used oil from food

service institutions. In addition, most researchers concentrated on the particular wavenumbers instead of the whole FTIR spectral data for characterizing the oil quality.

In this study the possibility of using the whole spectra from Fourier transform infrared attenuated total reflectance (FTIR-ATR) spectroscopy to classify and differentiate among various intensities of oil rancidity and to discriminate between good, marginal, and unacceptable frying oils was investigated.

MATERIALS AND METHODS

Frying oil samples were received from several local fast food restaurants in each frying cycle for 4 weeks. In addition, all oil samples were collected from the fryer used to fry only poultry products. All oil samples were kept at 4°C until further analysis using a FTIR-ATR and chemical methods to determine the level of oil rancidity.

Measuring the Quality of Oil

The differentiation among each frying oil sample based on its rancidity was examined using FTIR-ATR. All results were compared to their physical and chemical analyses including density, dielectric properties, free fatty acid content (FFA), and peroxide value (PV). Percentage of free fatty acid (FFA) was determined by alkaline titration according to AOCS method Ca 5a-40 (AOCS, 1989) and results were expressed as oleic acid percentage. Peroxide value (PV) was determined by AOAC method 965.33 (AOAC, 1995). Density was measured using a density meter (model DA-110M, Mettler Toledo, Kyoto Electronics Manufacturing, Japan) and dielectric constant was measured using FoodOil Sensor (model NI-20, Northern Technologies Intl. Corp., Lino Lakes, MN). Each measurement was replicated three times.

FTIR Measurement

The Nexus 870 FTIR spectrometer (Nicolet Instrument Corp., Madison, WI) with a deuterated tri-glycine sulfate (DTGS) detector was used for this experiment. A ZnSe ATR sampling accessory from Spectra-Tech (Shelton, CT) was used for ATR

measurements. ATR spectra were collected by using 256 scans/sample at 4 cm^{-1} resolution. Before scanning each sample, the background spectrum was taken with an empty ATR crystal and stored in the computer. An oil sample was pored onto the ATR ZnSe crystal for measurement. After each measurement, the ATR crystal was thoroughly cleaned with 1% Triton X-100 solution (Aldrich Chemical Co., Milwaukee, WI), followed by a hexane (Aldrich Chemical Co., Milwaukee, WI) wash. The washed crystal was then rinsed with distilled water, wiped with cotton, and dried under nitrogen gas after each measurement. Each sample was replicated three times.

Statistical Analysis

Data were subjected to analysis of variance using General Linear Model (GLM) and Least Significant Difference test (LSD) at 5% confidence level was performed to determine the differences among means using SAS procedures (SAS, 2000). FTIR data were analyzed using Principal Component Analysis (PCA) technique from WIN-DAS software to differentiate the quality of frying oil with regard to the responses of all sensors.

RESULTS AND DISCUSSION

The quality of frying oil samples collected from three different fast food services was evaluated. Dielectric constant, PV, FFA, and density of frying oils significantly ($P < 0.05$) increased as the oil age increased. Two of the restaurants decided to discard the frying oils after 9 days. Another discarded the used oils after using for 2 weeks. It was clear that the density of frying oils increased with an increase in the repeated use of old oils (Fig. 7.1). Normally, frying oils undergo extensive degradation and complex chemical transformations when heated. The presence of air and water accelerated the deterioration of frying oil (Clark and Serbia, 1991) and resulted in an increase in the number of polar molecules as confirmed by an increase in dielectric constant (Fig. 7.1) (Fritsch et al., 1979; Graziano, 1979; White, 1991).

During frying, oils are hydrolyzed to form free fatty acids and mono- and diglycerides and these compounds accumulated in the frying oil with repeated use. In addition, oils also oxidize to form hydroperoxide, conjugated dienoic acids, epoxides, hydroxides, and ketones. An increase in volatile compounds resulted in an increase in FFA content and PV in the oil samples (Fig. 7.2).

Measuring Oil Quality Using FTIR-ATR

FTIR spectra in the mid infrared region consist of fundamental and characteristic bands whose frequencies and intensities can clearly determine the relevant functional groups in frying oil samples. The spectra obtained from FTIR-ATR have strong C-H absorption between 3000 and 2850 cm^{-1} . Figure 7.3 clearly showed separate bands that correspond to asymmetrical C-H stretching (CH_2) at 2929 cm^{-1} and symmetrical C-H stretching (CH_2) at 2856 cm^{-1} with a weak shoulder at 2954 cm^{-1} caused by the methylene asymmetrical stretching band. Frying oil samples also showed the strong bands at 1749, 1464 and 1165 cm^{-1} that correspond to C=O (ester) stretching, C-H bending (scissoring), and C-O, CH_2 stretching, bending, respectively. Each type of oil samples including fresh, used, and discarded oils showed very similar FTIR spectra and the overall signal patterns looked similar to each other. However, the height of some specific bands was noticeable indicating the differences in quality.

Normally, the critical absorption bands associated with common oxidation end products from frying process could be observed in the region (3800–3200 cm^{-1}), OH stretching region. The peak at 3471 cm^{-1} has been reported to be associated with the OH stretching vibration of hydroperoxide and a weaker peak, or shoulder, in the region at 3300 cm^{-1} indicates the formation of FFA (Goburdhun et al., 2001). The correlation plots between FTIR spectra (at 3471 cm^{-1} and 3300 cm^{-1}) and chemical indexes (PV and FFA) showed the trend of higher absorbance bands at both regions (Fig. 7.4) with respect to deterioration of frying oils. This trend has also been confirmed by an increase in PV and FFA of oils over frying time (Fig. 7.2). The correlation (r) between FTIR absorbance at 3300 cm^{-1} and FFA was from 0.84 to 0.94 for oils from the three restaurants. Similarly,

the correlation between FTIR absorbance at 3471 cm^{-1} and PV was from 0.90 to 0.97 for oils from the same three restaurants.

However, the differences in the absorbance bands of each type of oil were small and difficult to classify the types of oil. To identify the FTIR spectra representing various levels of oil deterioration, the FTIR specialist was needed to interpret the data and associated them to quality and quantity measurements. In this study, the whole spectral data (wavenumbers between 4000 and 850 cm^{-1}) of various oil rancidity were used to characterize and classify the good, marginal, and unacceptable frying oils. Together with PCA covariance technique, the observation of PCA plots (between PC score 1 and 2) for all types of oils showed clearer and better performance in the differentiation and identification for the quality of frying oils. Each type of oil sample could be easily classified using FTIR-ATR (Fig. 7.5). In particular, the method successfully differentiated and identified the FTIR spectra between the discarded and fresh oils. As the results of PCA plots, the fresh oil clearly showed the different plot location from the discarded oil. These results showed that the difference in the FTIR spectra of the fresh and discarded oils were magnified and discriminated each other by chemometrics (PCA covariance technique). The plots of PC score 1 showed the marginal quality of frying oil from the good quality (located in one side) to the unacceptable quality (plotted in the opposite side of the graph) (Figure 7.6). As longer repeated use of the old oils, PCA plot gradually shifted the plot location from the good oil to the discarded one in the other side. These plots can be used by the frying operators to easily monitor the oil quality and confirm their decision when the oil should be discarded.

FTIR-ATR technique would eliminate the use and disposal of hazardous solvents and reagents required by the chemical methods. Further research must be investigated to more effectively utilize this equipment as a powerful tool in quality and process control in the fried food industry.

CONCLUSION

FTIR-ATR is another optional method for measuring oil rancidity. In conjunction with chemometrics, the various oil qualities can be effectively and successfully discriminated and identified from each other. The results of the FTIR-ATR studies were easily differentiated between fresh and discarded oils. Good correlation was found between chemical properties of oil samples and FTIR spectra. FTIR analysis provides a rapid means of evaluating the oxidative state of oil and of monitoring changes in oil undergoing thermal oxidative reactions.

REFERENCES

- AOAC. 1995. Official Methods of Analysis of AOAC International. 16th edition, vol. 2, Arlington, Virginia.
- AOCS. 1989. Official Methods and Recommended Practices of the American Oil Chemists' Society. 4th edition, Champaign, IL.
- Blumenthal, M.M. 1991. A new look at the chemistry and physics of deep fat frying. *Food Technol.* 45(2): 68-72, 94.
- Clark, W.L. and Serbia, G.W. 1991. Safety aspects of frying fats and oils. *Food Technol.* 45(2): 84-89, 94.
- Dubois, J., Van de Voort, F.R., Sedman, J., Ismail, A.A. and Ramaswamy, H.R. 1996. Quantitative fourier transform infrared analysis for anisidine value and aldehydes in thermally stressed oil. *J. Am. Oil Chemists' Soc.* 73(6): 787-794.
- Fritsch, C.W., Eggerg, D.C. and Magnuson, J.S. 1979. Changes in dielectric constant as a measure of frying oil deterioration. *J. Am. Oil Chemists' Soc.* 56(8): 746-750.
- Goburdhun, D., Jhaumeer-Laulloo, S. and Musruck, R. 2001. Evaluation of soy bean oil quality during conventional frying by FTIR and some chemical indexes. *Inter. J. of Food Sci. and Nutri.* 52: 31-42.
- Graziano, V.J. 1979. Portable instrument rapidly measures quality of frying fat in food service operations. *Food Technol.* 33(9): 50-57.
- Ma, K., Van de Voort, F.R., Sedman, J. and Ismail, A.A. 1997. Stoichiometric determination of hydroperoxides in fats and oils by Fourier transform infrared spectroscopy. *J. Am. Oil Chemists' Soc.* 74(8): 897-906.
- Melton, S.L., Jafar, S., Sykes, D. and Trigiano, M.K. 1994. Review of stability measurements for frying oils and fried food flavor. *J. Am. Oil Chemists' Soc.* 71(12): 1301-1308.
- Orthofer, F.T. 1988. Care of food service frying oils. *J. Am. Oil Chemists' Soc.* 65(9): 1417-1419.
- Orthofer, F.T., Gurkin, S. and Liu, K. 1996. Dynamic of frying. Ch. 11 in "*Deep frying. Chemistry, nutrition, and practical applications*". E. G. Perkins and M. D. Erickson (Ed.), p. 223-244. AOCS Press, Champaign, IL.

- Paradis, A. J. and Nawar, W.W. 1981. Evaluation of new methods for the assessment of used frying oils. *J. Food Sci.* 46: 449-451.
- SAS. 2000. *SAS User's Guide: Statistics*, Version 8 edition. SAS Institute Inc., Cary, NC, USA.
- Tan, Y.A., Ong, S.H., Berger, K.G., Onn, H.H. and Poh, B.L. 1985. A study of the cause of rapid color development heated refined palm oil. *J. Am. Oil Chemists' Soc.* 62(6): 999-1006.
- Tyagi, V.K. and Vasishtha, A.K. 1996. Changes in the characteristics and composition of oils during deep-fat frying. *J. Am. Oil Chemists' Soc.* 73(4): 499-506.
- Van de Voort, F.R., Sedman, J. and Ismail, A.A. 1993. A rapid FTIR quality control method for determining fat and moisture in high-fat products. *Food Chemistry.* 48: 213-221.
- Van de Voort, F.R., Ismail, A.A., Sedman, J., Dubois, J. and Nicodemo, T. 1994. The determination of peroxide value by Fourier transform infrared spectroscopy. *J. Am. Oil Chemists' Soc.* 71(9): 921-926.
- White, P.J. 1991. Methods for measuring changes in deep-fat frying oils. *Food Technol.* 45(2): 75-80.
- Yang, H. and Irudayaraj, J. 2000. Characterization of semisolid fats and edible oils by Fourier transform infrared photoacoustic spectroscopy. *J. Am. Oil Chemists' Soc.* 77(3): 291-295.

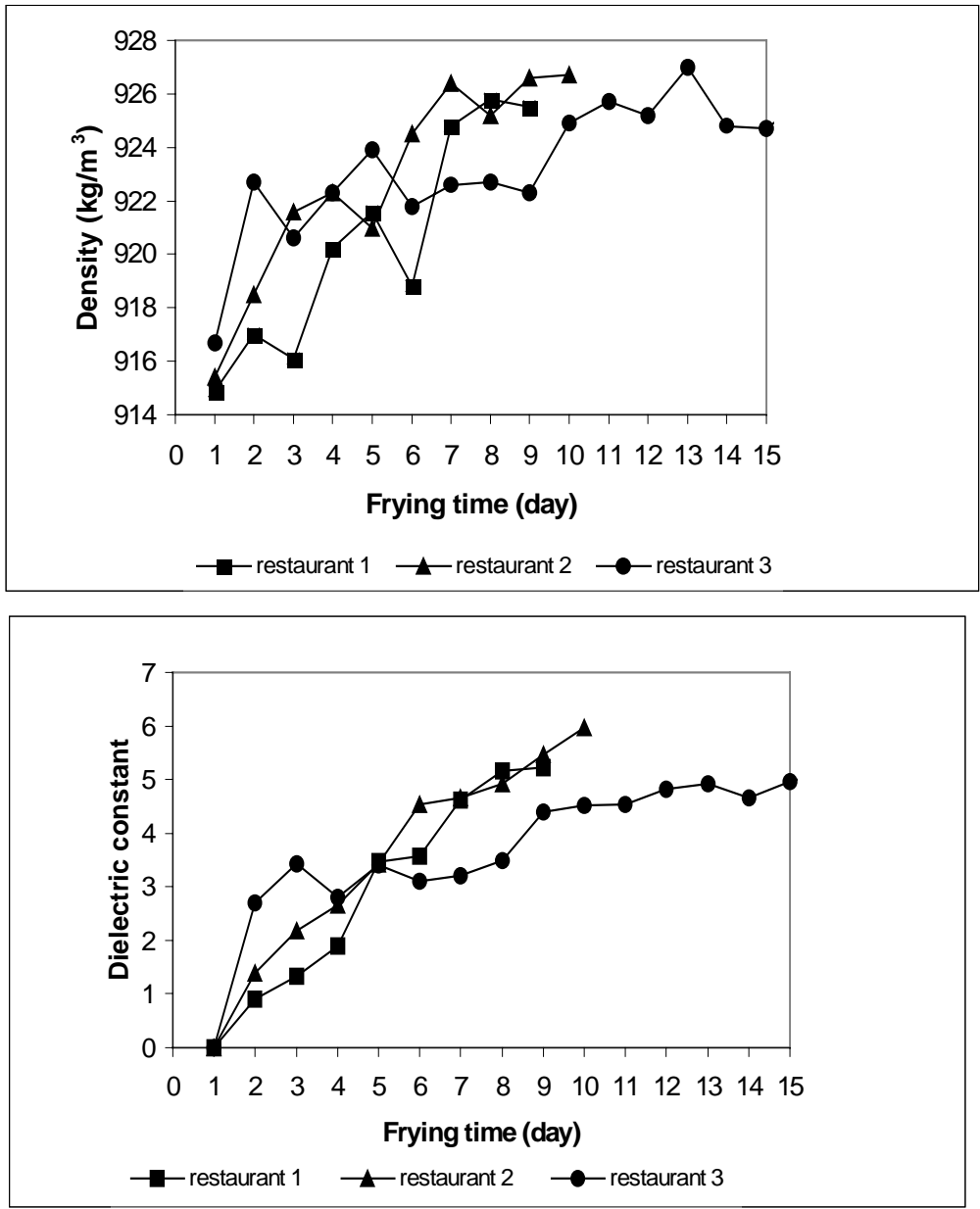


Figure. 7.1 Physical properties of frying oils collected from the different days of operation.

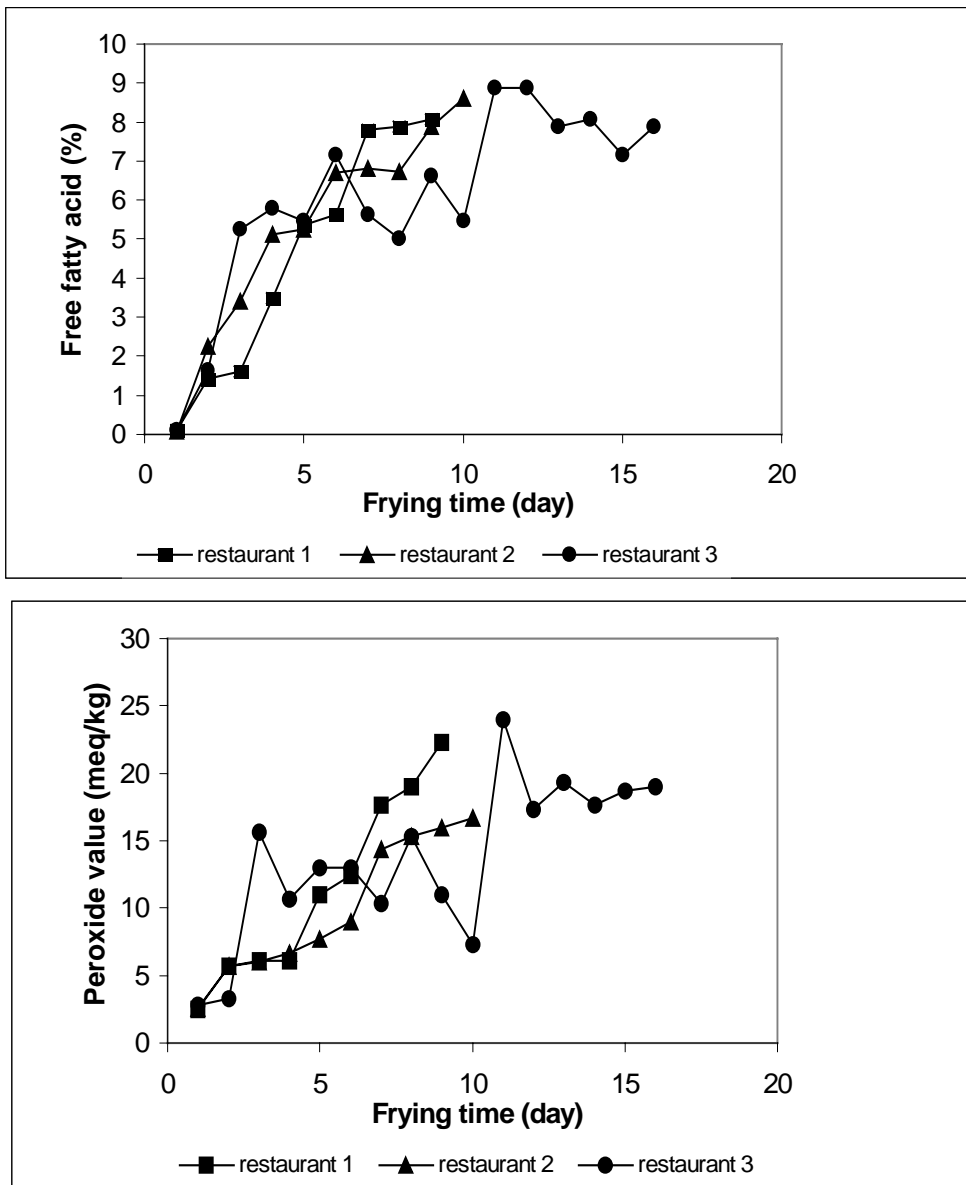


Figure 7.2 Chemical properties of frying oils collected from the different days of operation.

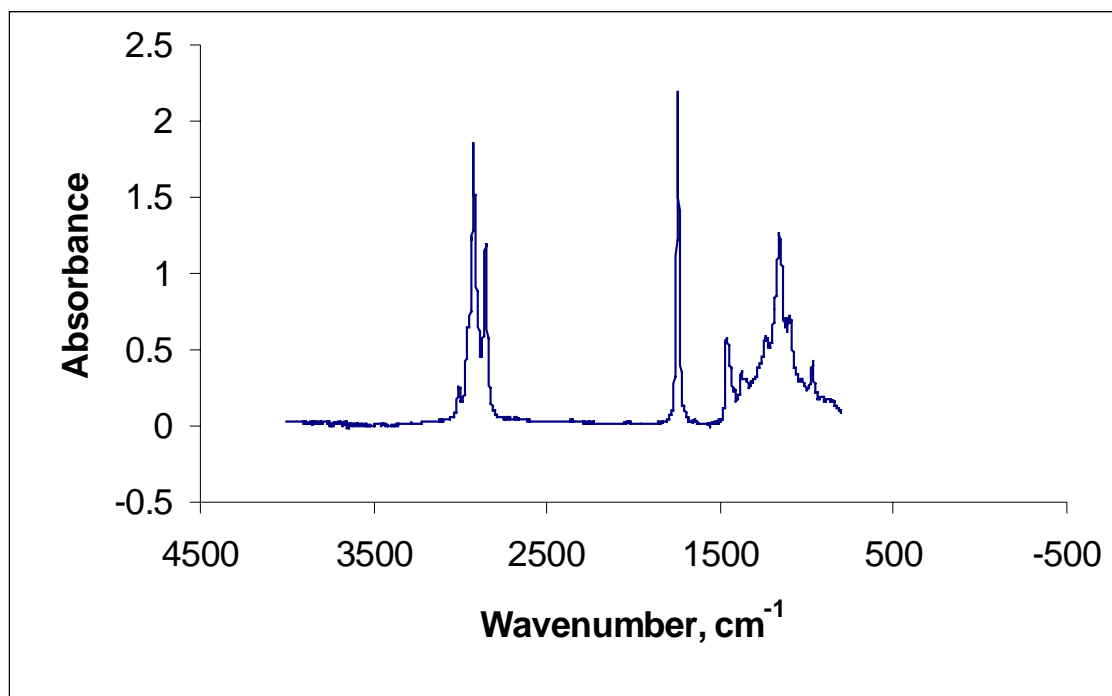


Figure 7.3 The FTIR-ATR spectra of frying oils in mid-infrared range.



Figure 7.4 The correlation between chemical properties (PV and FFA) and FTIR absorbance.

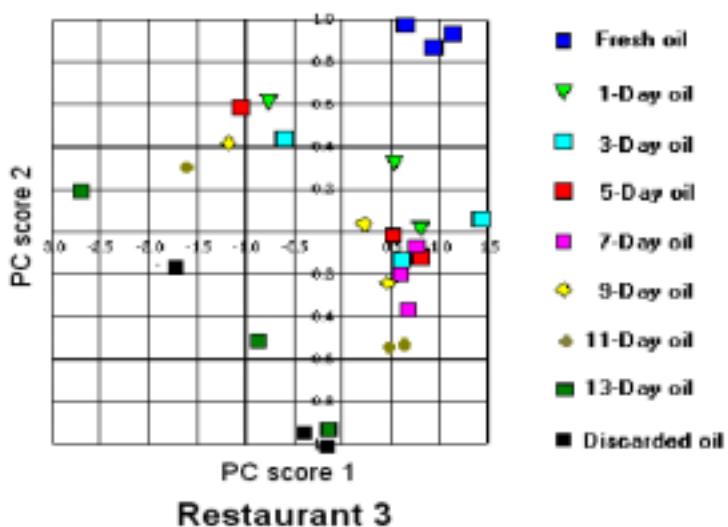
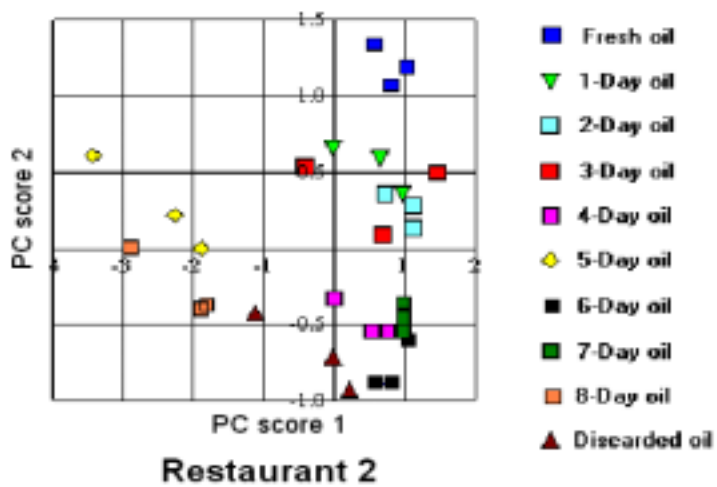
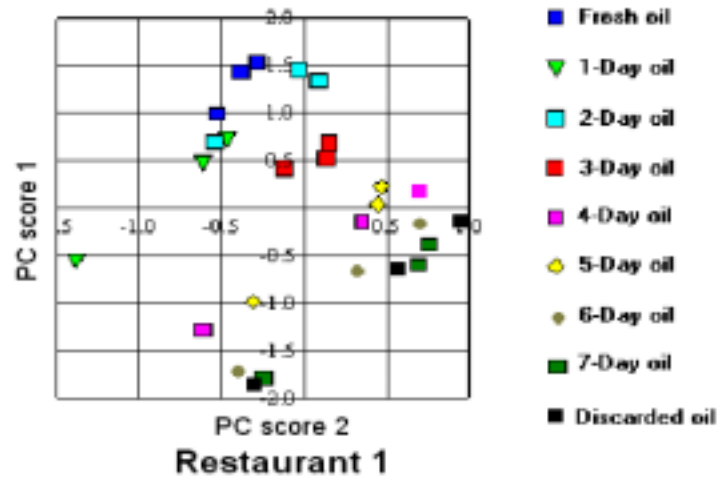


Figure 7.5 Principal component analysis plots for various types of oils collected from three different fast food services (between PC 1 and PC 2).

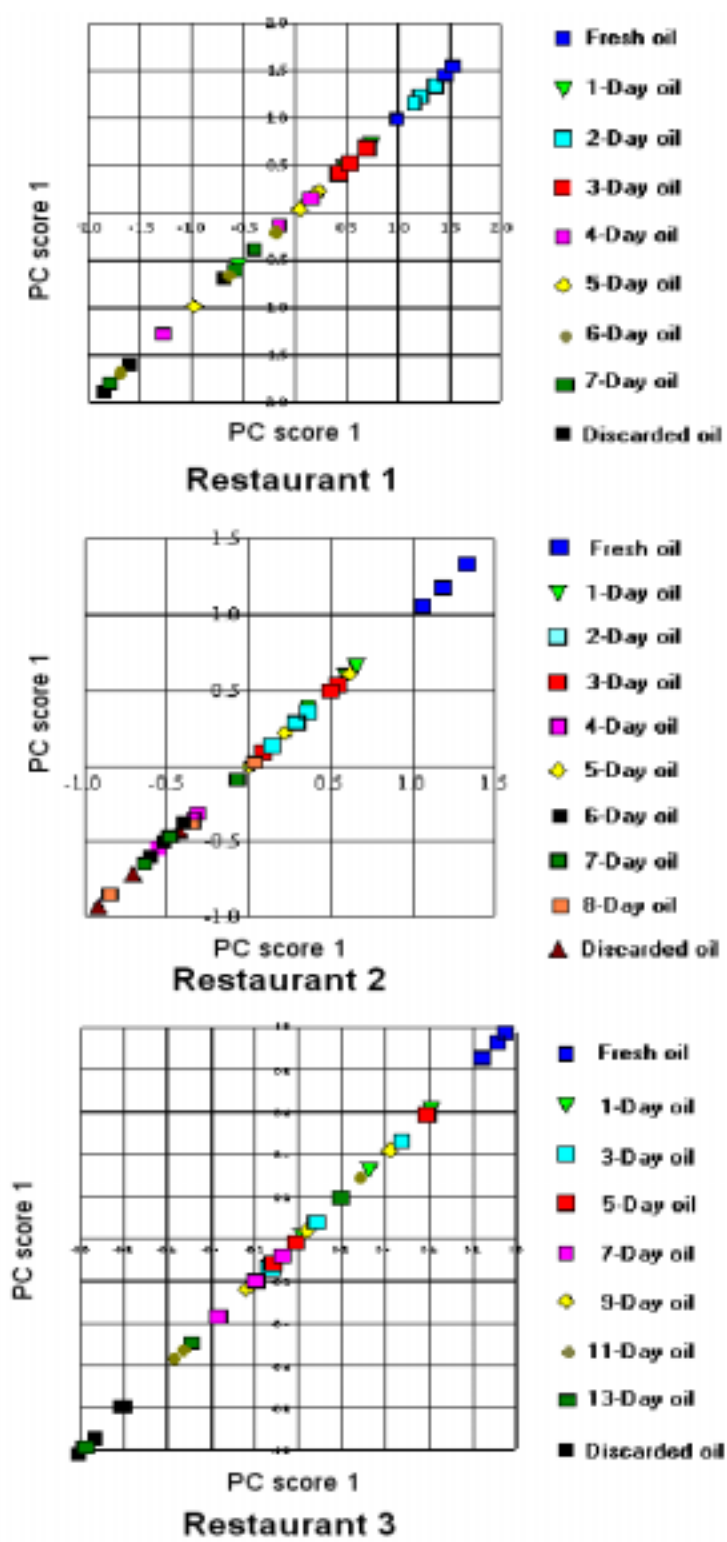


Figure 7.6 Principal component analysis plots for various types of oils collected from three different fast food services (between PC 1 and PC 1).

CHAPTER 8

The Effect of Pressure Conditions on The Deterioration of Frying Oil

ABSTRACT

Commercial pressure frying equipment used in fast food restaurants relies on the moisture released from the products to generate the pressure. This moisture can mix with the air, react with the hot oil and deteriorate the oil faster. Nitrogen gas has been introduced in the pressure fryer to substitute the steam generated from released moisture because frying with nitrogen can inhibit the contact of oil with air/water mixture. Previous studies demonstrated the feasibility of using nitrogen gas to pressurize the fryer and showed improvement in product quality. The effect of nitrogen gas used in pressure frying on the frying oil quality oil needs to be evaluated. In this work, experiments were conducted to study the effect of nitrogen gas on the deterioration of frying oil during pressure frying.

Oil samples were collected from the pressure fryer that fried chicken cutlets every 20 minutes at a temperature of 175°C and under pressure of 184 kPa for 20 batches/day. Physical and chemical changes of frying oils were determined. Density, dielectric constant, free fatty acid content (FFA), and peroxide value (PV) of frying oils collected from both nitrogen gas and traditional steam batches significantly ($P < 0.05$) increased with frying time. After the same frying time, the reused oils obtained from batch fried with nitrogen gas resulted in significantly lower dielectric constants, FFA, and PV than the system using steam. All oil samples were successfully discriminated and identified among each other in both systems, nitrogen gas and steam by the use of chemosensory system (QMB-6). In addition, the results from discriminant function analysis (DFA) plot also confirmed the oils collected from the pressure fryer using nitrogen gas were better in quality than the system using steam.

Keywords: nitrogen gas, steam, pressure fryer, frying oil quality, chemosensory system

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INTRODUCTION

The quality of the frying oil and the quality of the food fried in that oil are intimately related (Blumenthal, 1991). Frying oil quality influences oil absorption and the types of by-products and residues absorbed by food. Repeated use of frying oil produces undesirable constituents that may pose health hazards. It is known that frying oils used continuously or repeatedly at high temperatures in the presence of oxygen and water from the food being fried are subject to thermal oxidation, polymerization, and hydrolysis, and the resultant decomposition products adversely affect flavor and color of oils (Clark and Serbia, 1991; Tyagi and Vasishtha, 1996; White, 1991).

Several factors influence the quality of frying medium including air exposure, moisture exposure, stability of the oil to oxidation, contamination of frying oil with oil from the food being fried, and contamination from charred food particles primarily from the breading mixes used to coat fried foods (Orthofer, 1988). Deterioration of frying oils generally is followed by changes in free fatty acid level, color, or an increase in polarity of the oil (Melton et al., 1994; Orthofer, 1988; Orthofer et al., 1996; Paradis and Nawar, 1981; Tan et al., 1985; White, 1991). Thus, various criteria were used to judge when the frying oils should be discarded. In restaurants and food services, changes in physical properties of frying oils were used as indicator to measure oil quality (Moreira et al., 1999). For example, the frying oil may be discarded when the oil becomes dark, too much smoke, strong odor, grease texture, or when a persistent foam layer of specified thickness is observed (Moreira et al., 1999). However, before an operator sees such effects the oil has usually suffered considerable decomposition. In a food industry, not only physical tests but chemical tests were also used to measure oil quality including acidity, polymer content and/or total polar materials (Moreira et al., 1999; White, 1991). Oil is a significant cost in deep fat frying process. Thus, there is a recent trend in prolonging oil life. The food service institution is adopting various methods of maintaining the quality and increasing the useful life of frying oils by the use of active and passive filters, antioxidants, and proper maintenance of the fryer equipment (Lin et al., 1998; Orthofer, 1988; Rhee et al., 1992). In existing pressure frying equipment, moisture released from the fried products can mix with air and deteriorate the oil faster.

Recently, nitrogen gas has been used in the fried food industry to flush above the fryer to prevent the reactions between the air (oxygen) and the hot oil. Nitrogen gas has been introduced in the pressure fryer to substitute for steam generated from the released moisture. Nitrogen gas can prevent the contact of hot oil with an air/water mixture. Previous work by the authors demonstrated the feasibility of using nitrogen to pressurize the fryer. They also showed an improvement in fried product quality through moisture retention, juiciness, and texture in fried poultry products (Innawong et al., 2001a,b,c).

The effect of nitrogen gas used in pressure frying on the frying oil quality needed to be evaluated. In this work, experiments were conducted to study the effect of nitrogen gas on the deterioration of frying oil during pressure frying of breaded poultry products.

MATERIALS AND METHODS

The study was conducted with frozen, commercial breaded chicken cutlets obtained from Perdue Farms, Inc. Each 1.5 kg of sample was fried in 28.5 kg of commercial vegetable oil (Bakers & Chefs, North Arkansas Wholesale Company, Inc., Bentonville, AR). A batch of chicken cutlets were fried every 20 minutes at a temperature of 175°C and under pressure of 184 kPa using two pressure sources including nitrogen gas and steam released from the food for generating required pressure in a restaurant type pressure fryer (Model 500C, Henney Penney, Inc., Eaton, OH). In this study, the pressure fryer was modified by adding a nitrogen gas flow system (Innawong et al., 2001a) to maintain the set pressure.

For each frying cycle, the chicken samples were fried for 5 min and then the temperature of frying oil was turned down to 100°C for 10 min during unloading products. The 5-min gap between each frying cycle provided time for next batch preparation and permitted the pressure fryer to make up any loss in temperature. A typical experiment included an average of 30 s delay in closing and opening the vessel. Twenty batches of food were fried daily over a 7-hour period and for total of 7 days to simulate the frying condition commonly applied in the fast food services. The frying oil was filtered at the end of the operation to remove the disintegrated batter mixes out of the

oil and then the oil samples were collected and then kept at 4°C for further analysis. Fresh oil was added to the fryer each day after the oil samples had been collected. Thus, the oil in the fryer was always maintained at the 28.5 kg level (the recommendation level from the fryer manufacturer).

Measurement of Frying Oil Quality

The differentiation among frying oil samples regarding to rancidity was examined using a chemosensory system. All results were compared to their physical and chemical analyses including density, dielectric properties, free fatty acid content (FFA), and peroxide value (PV). The physical and chemical changes of frying oil were determined to represent the deterioration of abused oil due to high temperature and moisture from food during the frying process. Percentage of free fatty acid (FFA) was determined by alkaline titration according to AOCS method Ca 5a-40 (AOCS, 1989) and results were expressed as oleic acid percentage. Peroxide value (PV) was determined by AOAC method 965.33 (AOAC, 1995). Changes in density were measured using a density meter (model DA-110M, Mettler Toledo, Kyoto Electronics Manufacturing, Japan) and dielectric constant using Food Oil Sensor (model NI-20, Northern Technologies Intl. Corp., Lino Lakes, MN). Each measurement was replicated three times.

Off-Flavor

The chemosensory system (model QMB-6, Perkin Elmer, Norwalk, CT) connects to a HS40-XL auto sampler and consists of six different sensors differing in polarity. Sensor substrate of this instrument is a quartz-microbalance based sensor (bulk acoustic wave gas sensor). A change in mass of a chemical compound causes a change in frequency as indicated by each sensor. The sensibility in this type of sensor is 1.2 Hz/ng. For interpretation of signal sensor data, QMBSOFT-NT software was used.

An oil sample of 1.5 ml was placed into a 22-ml glass vial. Using a crimping tool, each sample vial was sealed with a fitted cap and septum. Each vial should be sealed tightly to prevent leaks and an uncharacteristic decrease in sensor signal. Then,

the sample vials were placed in the instrumental tray for analysis. In this study, sensor cell temperature was 25°C, sample temperature was 80°C, and HS-needle temperature was 100°C as specified by Innawong and Mallikarjunan (2001). The following time scheme including thermostat (60 min), zero level (30 s), pressurization (90 s), building-up (150 s), signal level (30 s), and purge (30 min) was used as time interval setting. These time intervals were recommended by the equipment manufacturer.

Statistical Analysis

All data except chemosensory system data were subjected to analysis of variance using General Linear Model (GLM) and Least Significant Difference (LSD) at 5 % confidence level was performed to determine the differences among means using SAS procedures (SAS, 2000). Chemosensor data were analyzed using Discriminant Function Analysis technique (DFA) from QMBSOFT-NT software to differentiate the frying oil quality from both nitrogen and steam systems.

RESULTS AND DISCUSSION

The physical and chemical properties of frying oil changed over frying time. The changes in oil color from both batches using nitrogen and steam were shown in figure 8.1. Density and dielectric constant of frying oil samples collected from both nitrogen gas and traditional steam batches significantly ($P < 0.05$) increased with frying time (Fig. 8.2). However, there are no significant difference in the density of frying oil between the use of nitrogen gas and steam in pressure frying. The density of frying oils from nitrogen and steam systems ranged from 917.8 to 920.8 kg/m³. On the other hand, dielectric constant of the oils collected from the nitrogen batch had significantly lower values than that from the steam batch (Fig. 8.2). Dielectric constant of 7-day old oil from the nitrogen batch was approximately 41% lower than that from the steam batch, 0.85 as compared to 1.2.

An increase in frying time significantly increased ($P < 0.05$) free fatty acid content (FFA) of frying oils collected from both nitrogen gas and steam batches (Fig. 8.3). FFA

of 7-day oil from nitrogen batch was significantly lower than the steam system (approximately 59%). The chemical changes of oil samples also were confirmed by a significant increase in peroxide value (PV). An increase in volatile compounds due to oxidation and hydrolysis during pressure frying resulted in an increase in FFA and PV in the oil samples.

Innawong et al. (2001a,b,c) reported that products fried with nitrogen gas had more moisture retention and juiciness in the core than the products fried with steam. As expected, pressure frying with nitrogen instead of steam directly decreased the moisture loss from fried products and subsequently prevented both thermal and oxidative decompositions of the oil as confirmed by the changes in physical and chemical properties of the frying oils.

The major chemical reaction occurring during commercial deep fat frying is hydrolysis. Moisture/steam reacts with triglycerides to form FFA, monoglycerides, diglycerides, and glycerol. The amount of FFA present and their breakdown products have an objectionable smell and finally develop off flavors. The substitution of steam by using nitrogen gas reduced the rate of hydrolysis as it effectively decreased the moisture loss from fried products. According to the changes of dielectric constant and FFA, the quality of 7-day oil from the nitrogen batch was similar to the quality of 3-day or 4-day oils from the steam batch.

After a discriminant function analysis (DFA) had been performed for data analysis, the DFA plot showed the qualities of oil samples collected from different frying times easily and visually discriminated and separated from each other (Fig. 8.4). The location plots gradually shifted from the quality of fresh oil to 7-day oil and represented the marginal quality of frying oil because the quality of fresh oil located on the one side of the discriminant plane and the quality of 7-day oil plotted in the end of the opposite side. An increase in frying time resulted in the proportional reduction of oil quality due to the deterioration of oil. Good discrimination and reproducibility were obtained to identify fresh and 7-day oils. As expected, the qualities of oil samples collected from the nitrogen batch were better than the steam batch when compared at the same frying time (Fig. 8.4). It was found that the quality of 7-day oil from nitrogen batch was similar to the quality of the oil between 3 and 5 days of frying from steam batch. The DFA plot

also confirmed the results of physical and chemical changes of oils between the use of nitrogen gas and steam.

CONCLUSION

The effect of nitrogen gas on the deterioration of frying oil in the pressure frying equipment was investigated. Density, dielectric constant, free fatty acid content (FFA), and peroxide value (PV) of frying oils collected from both nitrogen gas and traditional steam batches significantly ($P < 0.05$) increased with frying time. Compared with the same frying time, the quality of the reused oil collected from the nitrogen system was better than the steam system as evidenced by significantly lower dielectric constants, FFA, and PV. According to the results of DFA plots, each oil sample could be successfully discriminated and separated from each other with respect to various intensity of oil rancidity. As expected, the DFA plots also showed the oils collected from the pressure fryer using nitrogen gas were better in quality than the system using steam.

REFERENCES

- AOAC. 1995. Official Methods of Analysis of AOAC International. 16th edition, vol. 2, Arlington, Virginia.
- AOCS. 1989. Official Methods and Recommended Practices of the American Oil Chemists' Society. 4th edition, Champaign, IL.
- Blumenthal, M.M. 1991. A new look at the chemistry and physics of deep fat frying. *Food Technol.* 45(2): 68-72, 94.
- Clark, W.L. and Serbia, G.W. 1991. Safety aspects of frying fats and oils. *Food Technol.* 45(2): 84-89, 94.
- Fritsch, C.W., Eggerg, D.C. and Magnuson, J.S. 1979. Changes in dielectric constant as a measure of frying oil deterioration. *J. Am. Oil Chemists' Soc.* 56(8): 746-750.
- Graziano, V.J. 1979. Portable instrument rapidly measures quality of frying fat in food service operations. *Food Technol.* 33(9): 50-57.
- Innawong, B., and Mallikarjunan, P. 2001. The determination of frying oil quality using a chemosensory system. (In Preparation).
- Innawong, B., Mallikarjunan, P., and Cundiff, J.S. 2001a. The effect of pressure conditions on quality of chicken nuggets fried with constant frying time. (In Preparation).
- Innawong, B., Mallikarjunan, P., and Cundiff, J.S. 2001b. The effect of pressure conditions on quality of chicken nuggets fried with constant core temperature. (In Preparation).
- Innawong, B., Mallikarjunan, P., and Cundiff, J.S. 2001c. The effect of pressure conditions on quality of chicken fillets cooked for doneness. (In Preparation).
- Lin, S., Akoh, C.C. and Reynolds, A.E. 1998. The recovery of used frying oils with various adsorbents. *J. Food Lipids.* 5: 1-16.
- Melton, S.L., Jafar, S., Sykes, D. and Trigiano, M.K. 1994. Review of stability measurements for frying oils and fried food flavor. *J. Am. Oil Chemists' Soc.* 71(12): 1301-1308.

- Moreira, R.G., Elena Castell-Perez, M. and Barrufet, M.A. 1999. Frying oil characteristics. Ch. 3 in “*Deep-fat frying. Fundamentals and applications*”. Aspen Publishers, Inc., Gaithersburg, ML. p. 33-74.
- Orthoefer, F.T. 1988. Care of food service frying oils. J. Am. Oil Chemists’ Soc. 65(9): 1417-1419.
- Orthoefer, F.T., Gurkin, S. and Liu, K. 1996. Dynamic of frying. Ch. 11 in “*Deep frying. Chemistry, nutrition, and practical applications*”. E. G. Perkins and M. D. Erickson (Ed.), p. 223-244. AOCS Press, Champaign, IL.
- Paradis, A. J. and Nawar, W.W. 1981. Evaluation of new methods for the assessment of used frying oils. J. Food Sci. 46: 449-451.
- Rhee, K.S., Housson, S.E. and Ziprin, Y.A. 1992. Enhancement of frying oil stability by a natural antioxidative ingredient in the coating system of fried meat nuggets. J. Food Sci. 57(3): 789-791.
- SAS. 2000. *SAS User’s Guide: Statistics*, Version 8 edition. SAS Institute Inc., Cary, NC, USA.
- Tan, Y.A., Ong, S.H., Berger, K.G., Onn, H.H. and Poh, B.L. 1985. A study of the cause of rapid color development heated refined palm oil. J. Am. Oil Chemists’ Soc. 62(6): 999-1006.
- Tyagi, V.K. and Vasishtha, A.K. 1996. Changes in the characteristics and composition of oils during deep-fat frying. J. Am. Oil Chemists’ Soc. 73(4): 499-506.
- White, P.J. 1991. Methods for measuring changes in deep-fat frying oils. Food Technol. 45(2): 75-80.

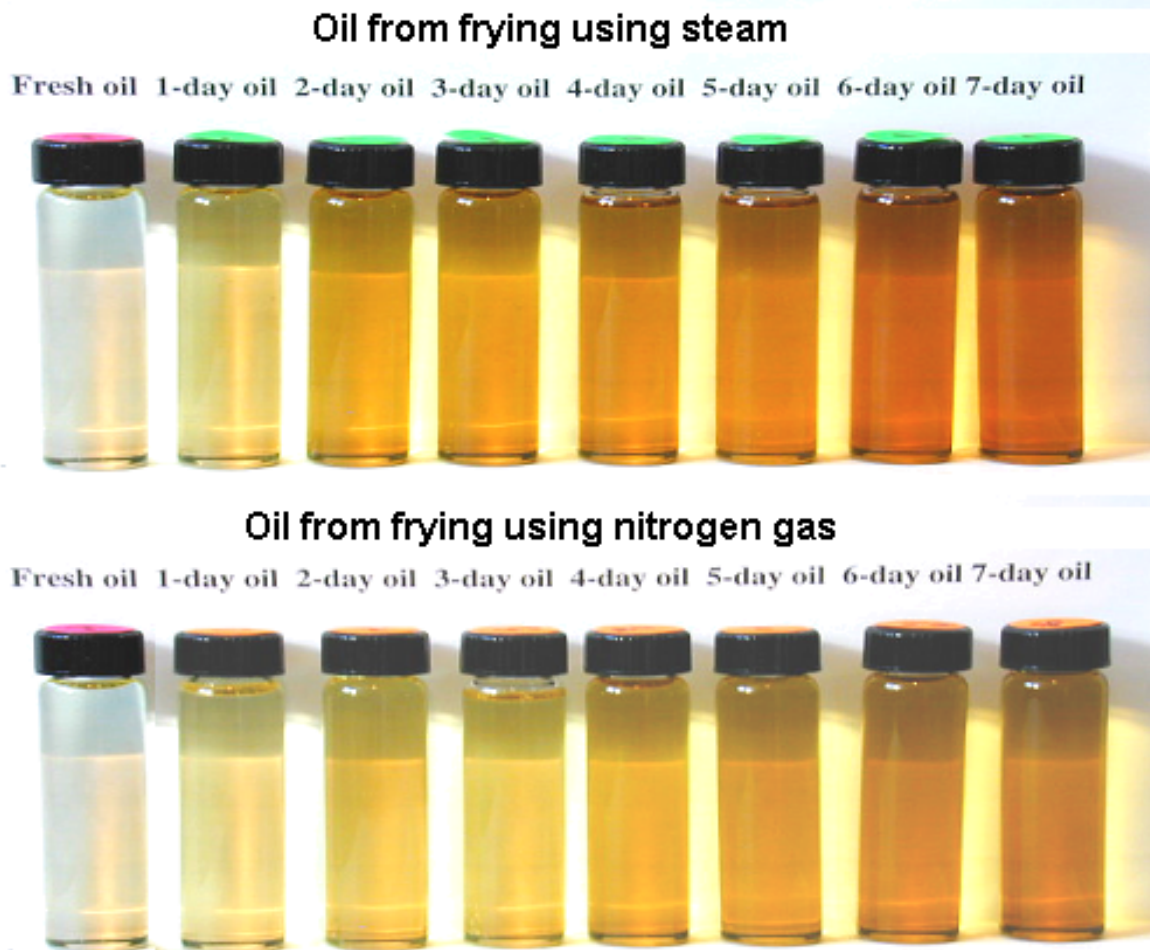


Figure 8.1 Oil samples collected from each frying day using steam and nitrogen gas to generate pressure in pressure frying system.

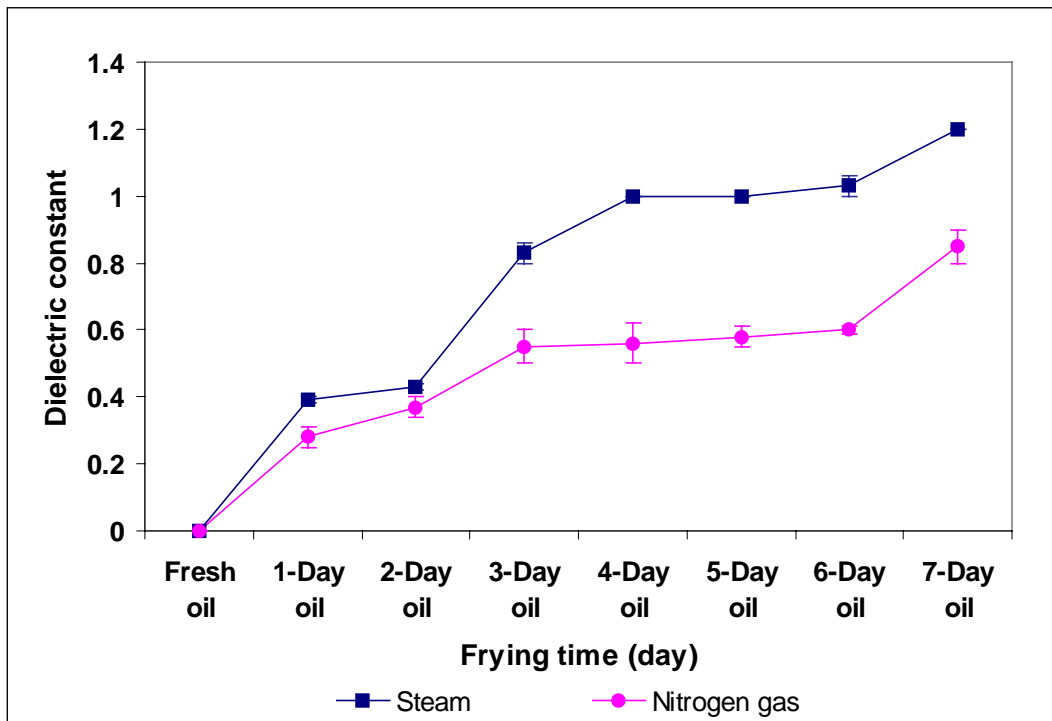
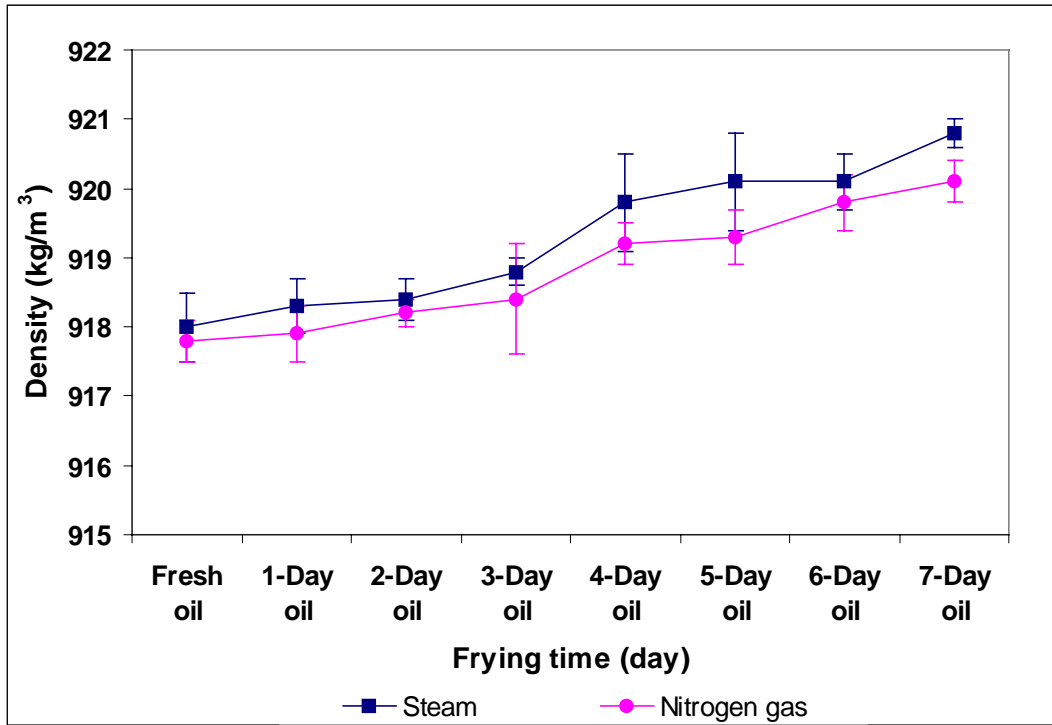


Figure 8.2 Physical properties of frying oils from steam and nitrogen batches.

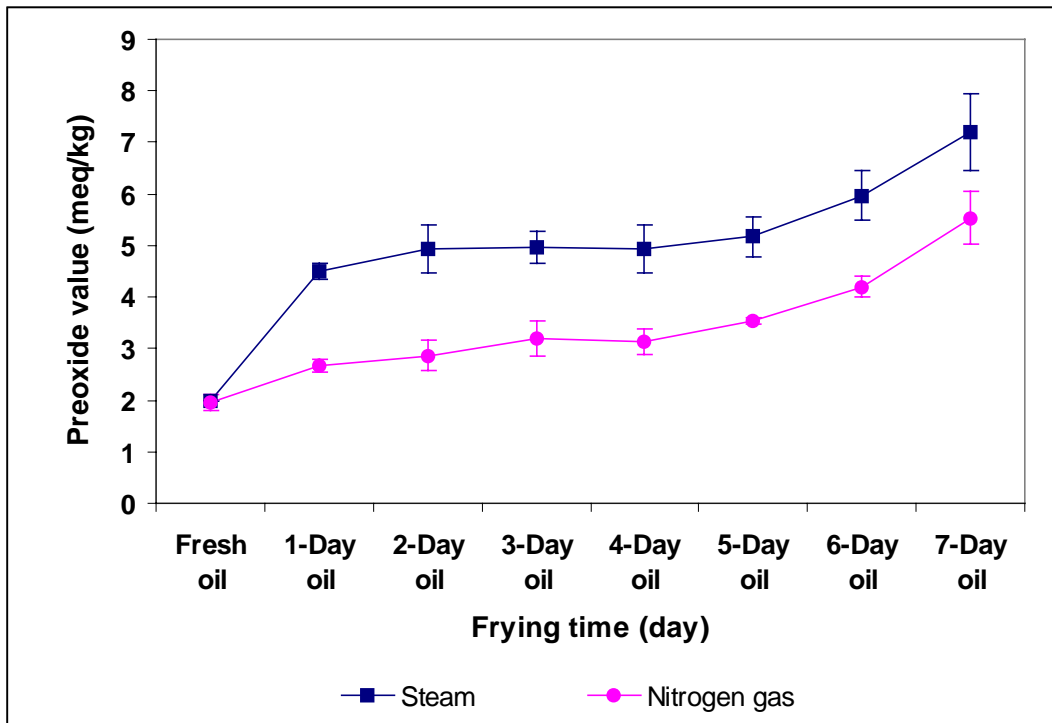
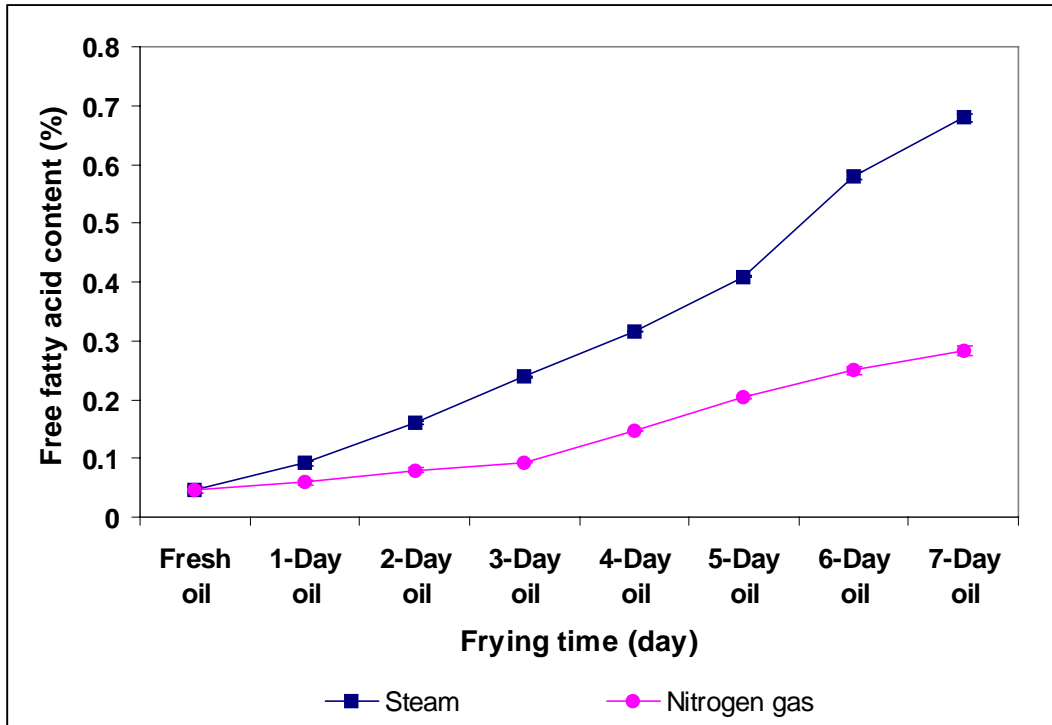


Figure 8.3 Chemical properties of frying oils from steam and nitrogen batches.

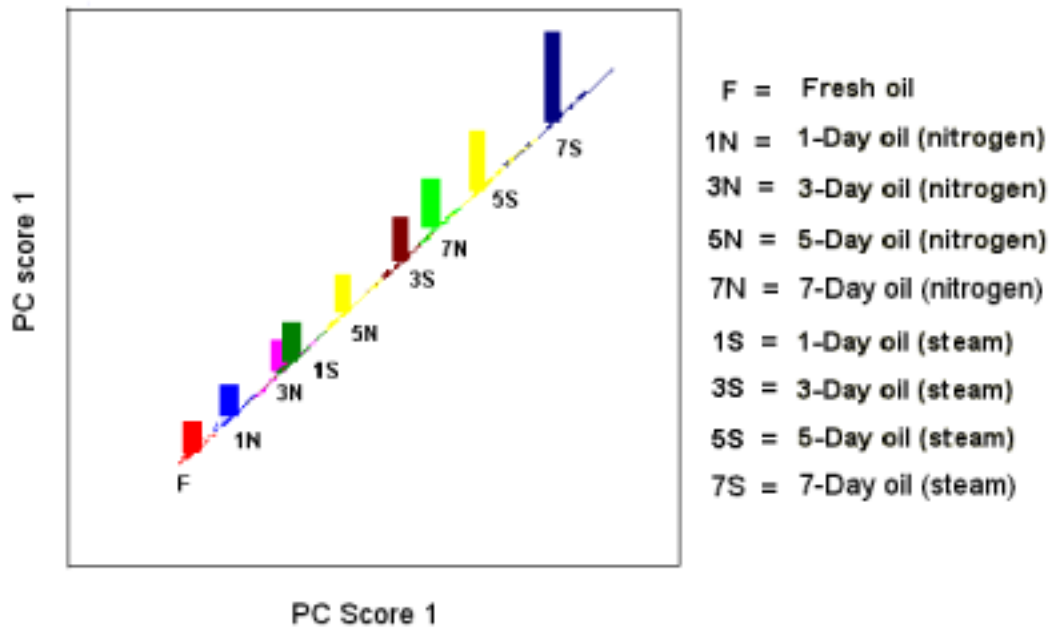


Figure 8.4 Graphic feature space plot (between PC1 and PC1) of all oil samples using the different sources of pressurized medium (steam and nitrogen gas).

CHAPTER 9

SUMMARY AND CONCLUSIONS

The pressure frying equipment currently used depends on the moisture released from the products to generate the desired cooking pressure. However, the moisture released from the products mixes with air and can deteriorate the oil faster. As this method relies on the amount of moisture/steam for generating pressure, the use of this equipment is also limited to situations where a large food load is fried in a single batch. To develop a pressure frying method that does not depend on the product load, the potential of nitrogen gas as a pressurizing medium to replace steam released from the products was investigated.

In this dissertation, the main objectives were to study the effect of nitrogen gas and steam on fried product quality and frying oil quality. To conduct the research, this dissertation was divided into three sections. First, experiments were conducted to study the effect of frying temperature, pressure and source of pressure including nitrogen gas and steam released from the products on the quality of fried poultry products. Various types of food products were considered including chicken nuggets (raw and par-fried products) and breaded chicken fillets. In addition, the various processing parameters such as frying temperatures (150°C, 175°C and 190°C) and pressures (101, 163, and 184 kPa) were selected to obtain the desirable characteristics of fried products. The quality attributes of the fried products were determined.

Frying temperature and pressure affected fried food quality. An increase in frying pressure resulted in a more tender, juicier product with less oil uptake due to the reduction in moisture loss. An increase in frying oil temperature resulted in more moisture loss, more oil uptake in crust, less tender and juicier products ($P < 0.05$). Compared with the use of steam released from food, frying under nitrogen gas provided similar or better quality fried products in terms of moisture retention, juiciness, and texture.

For the second part, this study attempted to develop new techniques to measure frying oil quality using (1) a chemosensory system, and (2) FTIR-ATR equipment. This

study was conducted to determine the possibility of using these measurements to differentiate among varying intensities of oil rancidity and investigate discrimination and identification between good, marginal, and unacceptable frying oils. The frying oils were collected from several food service institutions and all the oil samples were obtained from the fryer that fried only poultry products. The physical and chemical changes of frying oils were determined and associated with the results from the chemosensory and FTIR-ATR systems.

Regarding to the results from chemosensory and FTIR-ATR analyses, it was found that the differences in quality of frying oil were successfully and effectively discriminated and classified with respect to various deterioration states of frying oil. In conjunction with chemometrics, the chemosensory system and FTIR-ATR studies showed good discrimination and stability for identification between acceptable and unacceptable frying oils with regard to rancidity. Good correlations (range from 0.84 to 0.97) were found between the changes in physical and chemical properties and chemosensory and FTIR-ATR responses. From this study, these developed techniques are very useful to determine frying oil quality over time because of its speed, reliability, and accuracy.

For the last section, experiments were conducted to study the effect of nitrogen and steam on the frying oil quality. The oils were collected from the pressure fryer that fried 20 batches of chicken per day every 20 minutes at a temperature of 175°C and under pressure of 184 kPa. The changes in physical and chemical properties of frying oil were determined.

From the study, it was found that density, dielectric constant, free fatty acid content, and peroxide value of frying oils collected from both batches using nitrogen gas and traditional steam significantly ($P < 0.05$) increased with frying time. Compared with the same day of frying, the reused oils from the fryer using nitrogen gas was better in quality than the system using steam as evidenced from the physical and chemical measurements. In conjunction with the use of chemosensory system, the results of DFA plots also confirmed the oils collected from the pressure fryer using nitrogen gas were better in quality than the system using steam.

For further study, the pressure fryer should be modified by a nitrogen gas recycle system. This should be done because it potentially can reduce the cost of nitrogen gas. To obtain a more accurate result, the basket lifting system to lift products out of the oil should be added in the future. Experiments also need to be performed using 'air' as the pressurizing medium to study the effects of oxygen present in the air on frying oil quality. In addition, sensory evaluation of the fried products between nitrogen and steam batches has to be investigated in the future.

APPENDIX

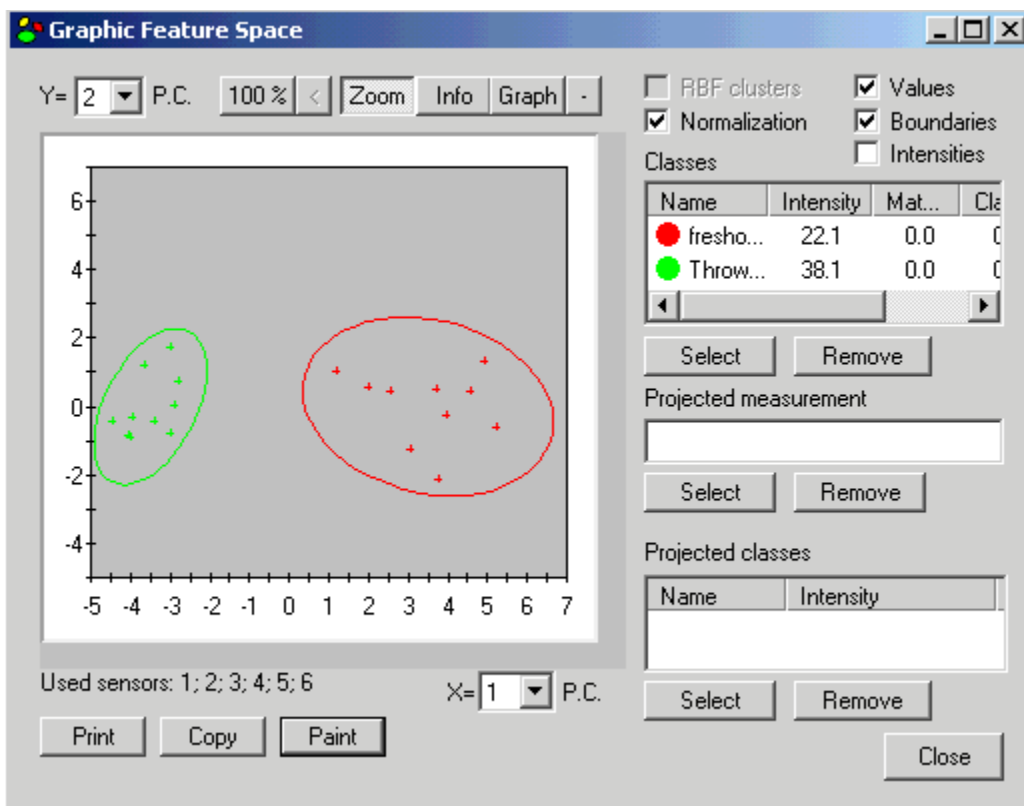


Figure. A.1 Graphic feature space plot between fresh and discarded oils using sample temperature 100°C and sensor cell temperature 25°C.

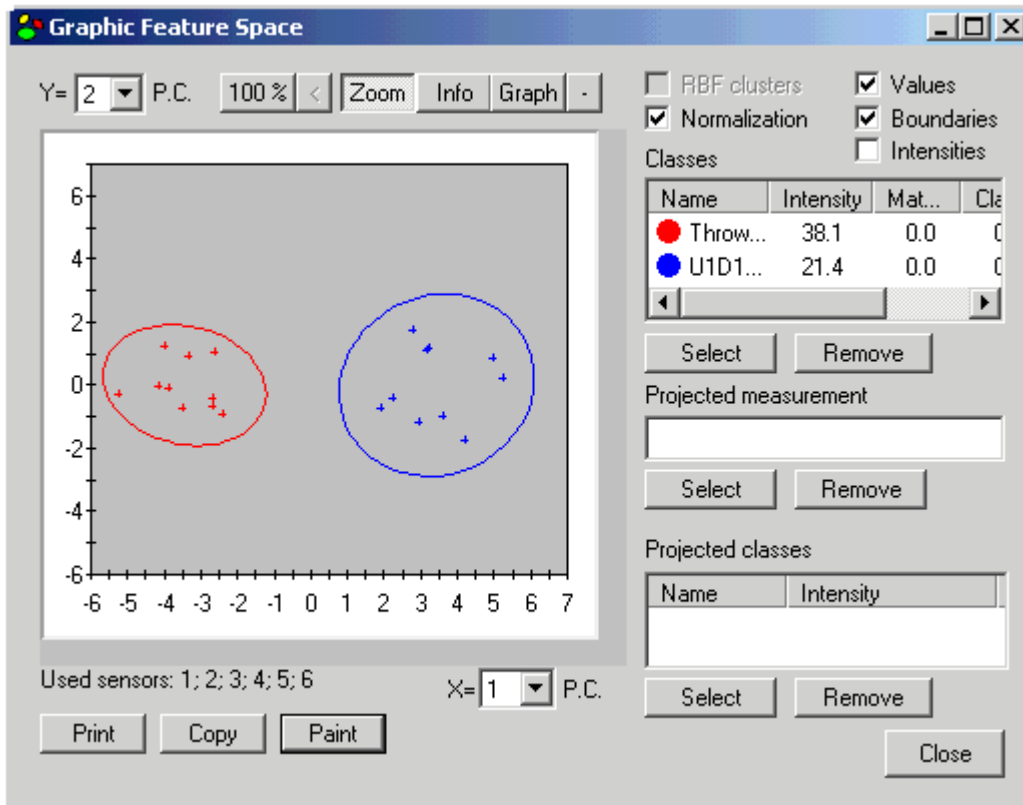


Figure A.2 Graphic feature space plot between 1-day used and discarded oils using sample temperature 100°C and sensor cell temperature 25°C.

Table A.1 Chemical and physical properties of oil sample collected from local fast food restaurant no.1.

Types of oil	Density (kg/m ³)	Dielectric constant	Free fatty acid (%)	Peroxide value (meq/kg)
Fresh oil	914.9 ^a ± 0.9	0.00 ^a ± 0.00	0.10 ^a ± 0.03	2.47 ^a ± 0.01
1-Day oil	917.0 ^c ± 0.2	0.90 ^b ± 0.02	1.43 ^b ± 0.58	5.67 ^b ± 0.31
2-Day oil	916.1 ^b ± 0.1	1.34 ^c ± 0.56	1.61 ^b ± 0.81	6.13 ^b ± 0.00
3-Day oil	920.2 ^e ± 0.5	1.90 ^d ± 0.01	3.49 ^c ± 1.21	6.13 ^b ± 0.27
4-Day oil	921.6 ^f ± 0.3	3.47 ^e ± 0.12	5.37 ^d ± 1.00	11.00 ^c ± 0.00
5-Day oil	918.8 ^d ± 0.2	3.58 ^e ± 0.03	5.64 ^d ± 1.36	12.47 ^c ± 0.27
6-Day oil	924.8 ^g ± 0.2	4.62 ^f ± 0.07	7.79 ^e ± 0.58	17.67 ^d ± 0.27
7-Day oil	925.8 ^h ± 0.3	5.17 ^g ± 0.06	7.88 ^e ± 1.00	19.00 ^d ± 0.31
Discarded oil	925.5 ^h ± 0.3	5.23 ^g ± 0.06	8.06 ^e ± 0.58	22.33 ^e ± 0.27

^{abc} means within a column with unlike superscript letters are significantly different (P<0.05)

Table A.2 Chemical and physical properties of oil sample collected from local fast food restaurant no.2.

Types of oil	Density (kg/m ³)	Dielectric constant	Free fatty acid (%)	Peroxide value (meq/kg)
Fresh oil	915.4 ^a ± 0.2	0.00 ^a ± 0.00	0.09 ^a ± 0.11	2.54 ^a ± 0.01
1-Day oil	918.5 ^b ± 0.3	1.40 ^b ± 0.06	2.24 ^b ± 0.58	5.67 ^b ± 0.16
2-Day oil	921.6 ^d ± 0.3	2.17 ^c ± 0.06	3.40 ^c ± 0.15	6.00 ^{bc} ± 0.16
3-Day oil	922.3 ^e ± 0.6	2.67 ^d ± 0.15	5.11 ^d ± 0.58	6.67 ^{cd} ± 0.00
4-Day oil	921.0 ^c ± 0.1	3.43 ^e ± 0.12	5.25 ^d ± 0.58	7.67 ^d ± 0.15
5-Day oil	924.5 ^f ± 0.3	4.53 ^f ± 0.06	6.69 ^e ± 0.06	9.00 ^e ± 0.23
6-Day oil	926.4 ^h ± 0.1	4.67 ^g ± 0.06	6.81 ^e ± 0.58	14.33 ^f ± 0.31
7-Day oil	925.2 ^g ± 0.2	4.93 ^h ± 0.06	6.72 ^e ± 0.58	15.33 ^{fg} ± 0.27
8-Day oil	926.6 ^h ± 0.2	5.47 ⁱ ± 0.06	7.88 ^f ± 1.73	16.00 ^{gh} ± 0.41
Discarded oil	926.7 ^h ± 0.2	5.97 ^j ± 0.06	8.60 ^g ± 1.15	16.67 ^h ± 0.00

^{abc} means within a column with unlike superscript letters are significantly different (P<0.05)

Table A.3 Chemical and physical properties of oil sample collected from local fast food restaurant no.3.

Types of oil	Density (kg/m ³)	Dielectric constant	Free fatty acid (%)	Peroxide value (meq/kg)
Fresh oil	916.7 ^a ± 1.1	0.00 ^a ± 0.00	0.11 ^a ± 0.01	2.77 ^a ± 0.15
1-Day oil	922.7 ^b ± 0.1	2.70 ^b ± 0.17	1.64 ^b ± 0.01	3.30 ^a ± 0.10
2-Day oil	920.6 ^d ± 0.5	3.43 ^d ± 0.15	5.25 ^c ± 0.15	15.63 ^e ± 0.55
3-Day oil	922.3 ^b ± 0.3	2.80 ^b ± 0.15	5.78 ^d ± 0.67	10.67 ^c ± 1.15
4-Day oil	923.9 ^e ± 0.2	3.40 ^d ± 0.00	5.46 ^{cd} ± 0.16	13.00 ^d ± 1.00
5-Day oil	921.8 ^c ± 0.2	3.10 ^c ± 0.10	7.17 ^f ± 0.16	13.00 ^d ± 1.00
6-Day oil	922.6 ^d ± 0.2	3.20 ^c ± 0.00	5.64 ^d ± 0.27	10.33 ^c ± 1.53
7-Day oil	922.7 ^d ± 0.2	3.50 ^d ± 0.10	5.02 ^c ± 0.31	15.33 ^{fg} ± 1.53
8-Day oil	922.3 ^f ± 0.1	4.40 ^e ± 0.10	6.63 ^e ± 0.31	11.00 ^c ± 1.00
9-Day oil	924.9 ^b ± 0.2	4.52 ^e ± 0.06	5.46 ^{cd} ± 0.11	7.30 ^b ± 0.58
10-Day oil	925.7 ^{gh} ± 0.2	4.53 ^{ef} ± 0.06	8.88 ^h ± 0.27	24.00 ^h ± 2.00
11-Day oil	925.2 ^{fg} ± 0.3	4.83 ^g ± 0.06	8.87 ^h ± 0.27	17.33 ^{ef} ± 1.15
12-Day oil	927.0 ⁱ ± 0.1	4.93 ^g ± 0.06	7.88 ^g ± 0.31	19.33 ^g ± 1.15
13-Day oil	924.8 ^f ± 0.2	4.67 ^f ± 0.06	8.06 ^g ± 0.27	17.67 ^{fg} ± 0.58
14-Day oil	924.7 ^f ± 0.1	4.97 ^g ± 0.06	7.17 ^f ± 0.62	18.67 ^{fg} ± 1.15
Discarded oil	925.8 ^h ± 0.3	5.17 ^h ± 0.06	7.88 ^g ± 0.31	19.00 ^{fg} ± 1.00

^{abc} means within a column with unlike superscript letters are significantly different (P<0.05)

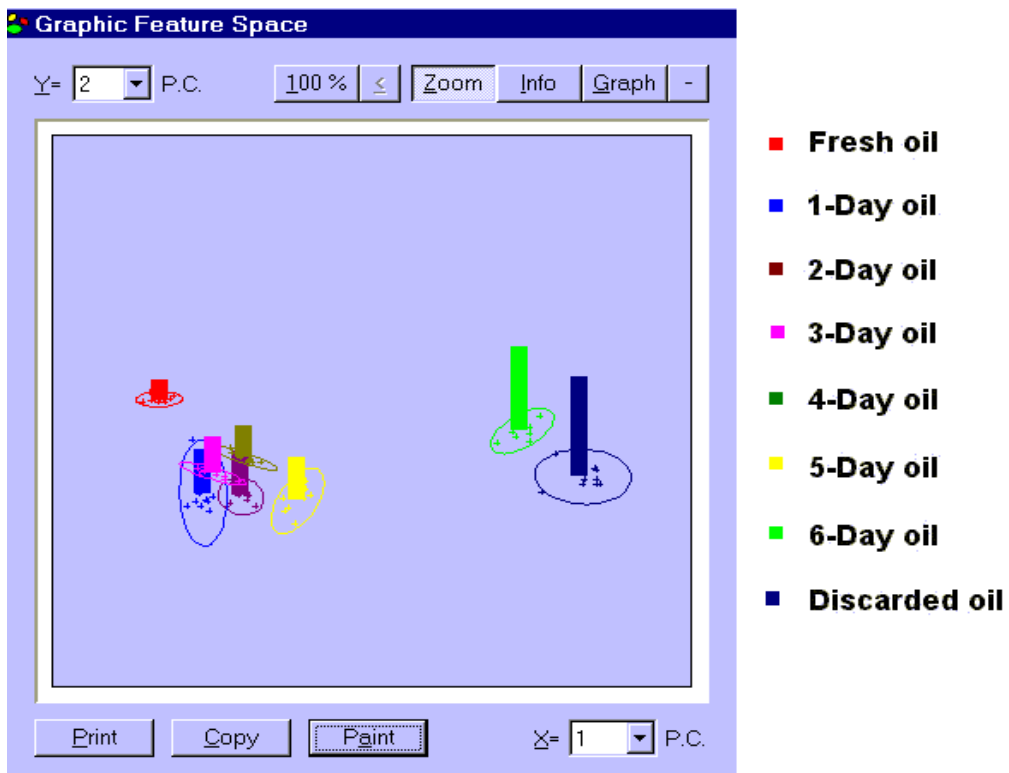


Figure A.3 Graphic feature space plot (between PC1 and PC2) of oil samples collected from the steam batch.

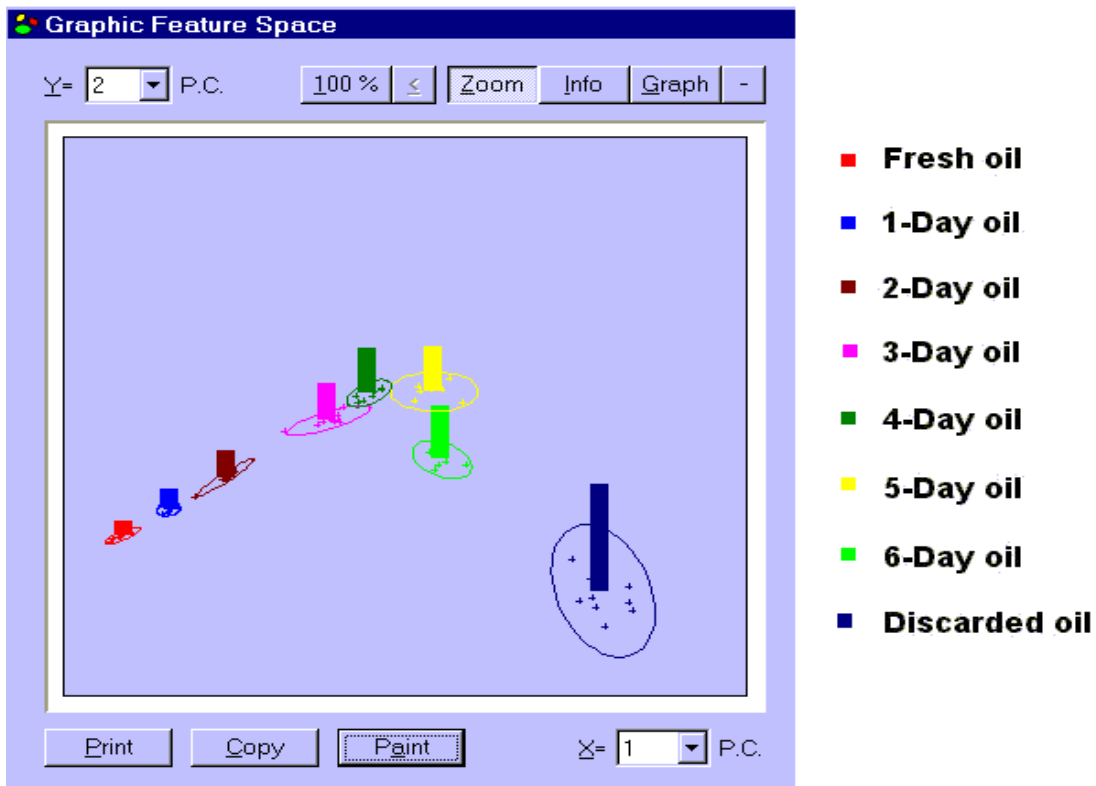


Figure A.4 Graphic feature space plot (between PC1 and PC2) of oil samples collected from the nitrogen batch.

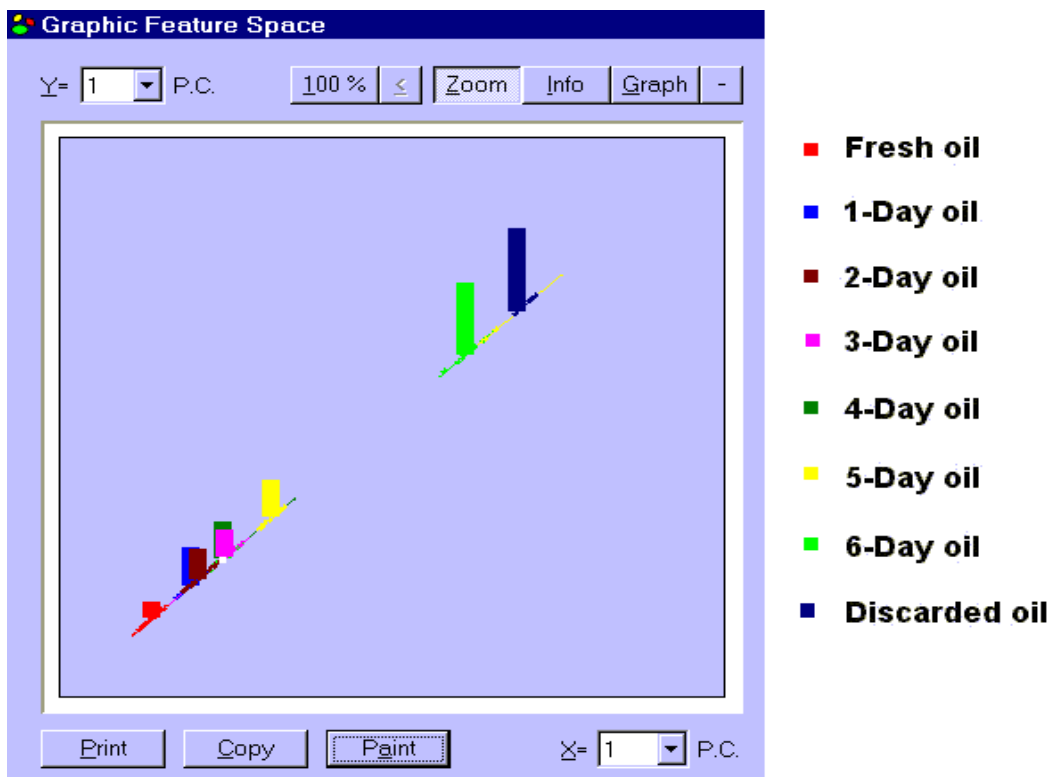


Figure A.5 Graphic feature space plot (between PC1 and PC1) of oil samples collected from the steam batch.

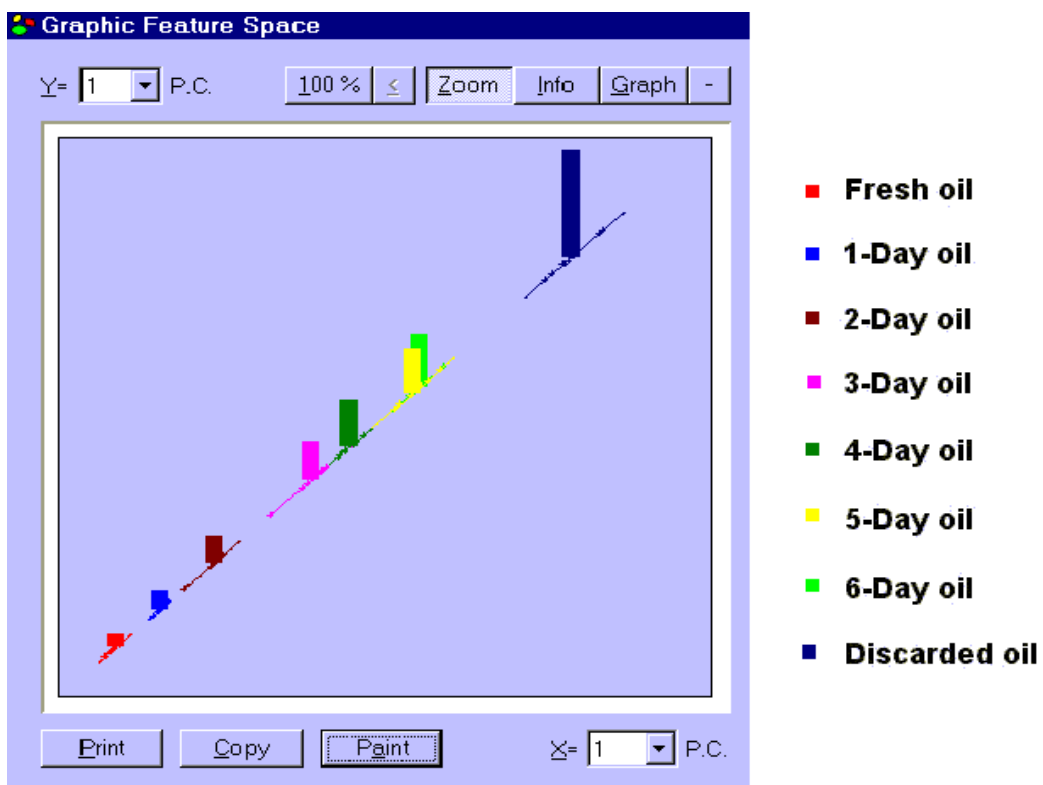


Figure A.6 Graphic feature space plot (between PC1 and PC1) of oil samples collected from the nitrogen batch.

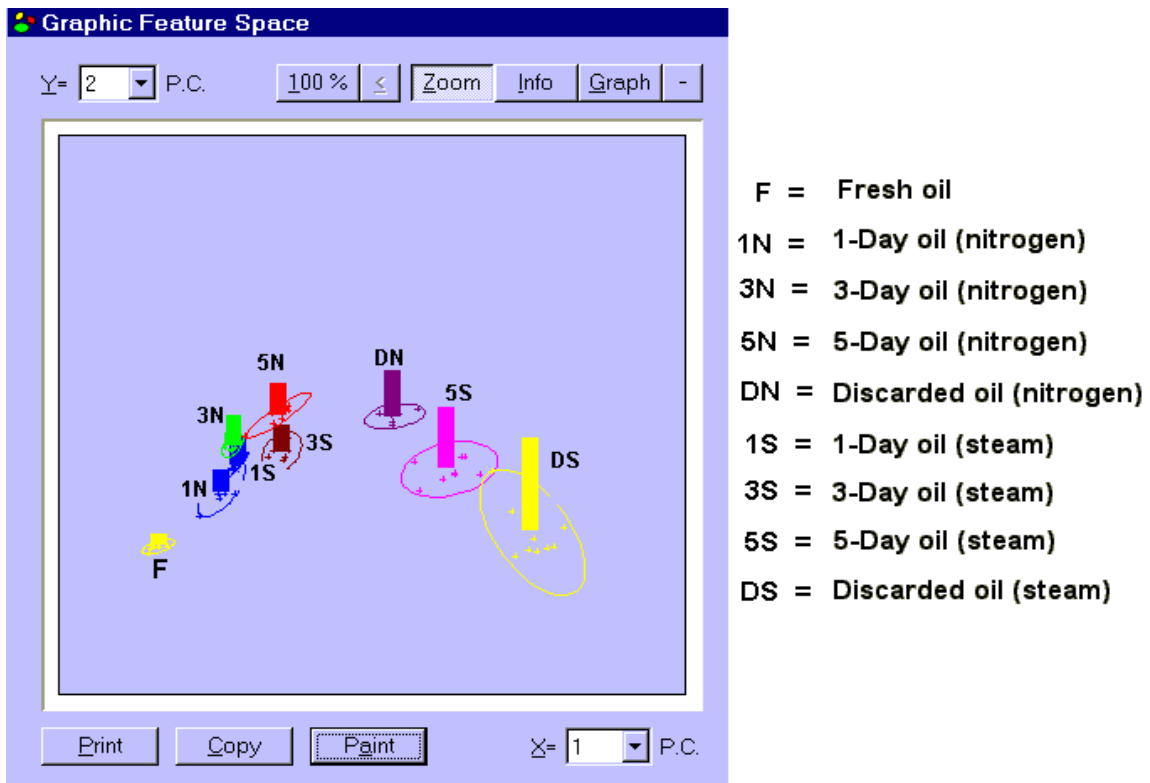


Figure A.7 Graphic feature space plot (between PC1 and PC2) of all oil samples collected from both steam and nitrogen batches.

VITA

The author, Bhundit Innawong, was born January 1, 1970 in Thailand. He graduated with a Bachelor of Science degree in Food Science from Kasetsart University in Bangkok, Thailand in 1992. After graduation, Bhundit had opportunity to work with the Dole Company as project supervisor in the preparation department for 2 years. In 1994, he received scholarship from his government in 1995 to study in USA. He graduated with a Master of Science degree in Food Science and Technology from Virginia Polytechnic Institute and State University in 1998. He began pursuing Doctor of Philosophy degree in Biological Systems Engineering department at Virginia Polytechnic Institute and State University.