TEXTURAL AND MASS TRANSFER CHARACTERISTICS OF CHICKEN NUGGETS DURING DEEP FAT FRYING AND OVEN BAKING

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ABSTRACT

The effects of deep fat frying and oven baking on mass transfer (moisture loss and oil uptake), color and textural characteristics of chicken nuggets were studied. Deep fat frying was performed at three oil temperatures, namely 150, 170 and 190°C. The frying times were 1, 2, 3 and 4 min. Oven baking was accomplished at three temperature levels: 200, 220, and 240°C, and the baking times were 10, 15, 20 and 25 min.

Moisture content of the breading portion of the fried chicken nuggets decreased following a typical drying curve and ranged from 0.90 to 0.22 g/g (db), while the moisture content of the core portion of the chicken nuggets decreased almost linearly and ranged from 1.96 to 1.4 g/g (db). Fat contents of the breading and core portions increased linearly with time. Generally, frying temperature significantly affected the moisture contents of the breading and core. It also affected the fat content of the core but not that of the breading. The moisture content of the breading portion of the baked chicken nuggets ranged from 0.90 to 0.18 g/g (db) following patterns similar to those from fried samples. Meanwhile, the moisture content of the core portion of the baked chicken nuggets did not change except at later stages of baking and it ranged from 2 to 0.87 g/g (db). Moisture contents in the breading and core portions decreased significantly with higher baking temperature.

In deep fat frying, the lightness (L) and yellowness (b) parameters decreased with longer frying time and higher frying temperatures while the redness (a) parameter increased with frying time and temperature. During oven baking, the lightness and

yellowness parameters increased then decreased with baking time. The effect of baking temperature was significant.

Puncture tests were performed on the cooked chicken nuggets. The maximum load of the control samples was 0.6 N. It increased upon frying to reach up to 6.1 N, while with oven baking it went up to 7.36 N. The effect of cooking time and temperature, whether in frying or baking, proved to be significant on the maximum load values. These values increased significantly with cooking time and with higher cooking temperatures.

A solution to Fick's second law of diffusion, assuming infinite slab geometry, was used to model the moisture loss from the breading portion of the chicken nuggets. The obtained model parameters were used to calculate the moisture diffusivities. In the case of deep fat frying the moisture diffusivities were 2.1, 2.9 and 2.5 $\times 10^{-9}$ m^2/s for the frying temperatures of 150, 170 and 190°C, respectively. While the moisture diffusivities obtained in the case of oven baking were 1.9, 2.3 and 3.16 $\times 10^{-10}$ m^2/s for the baking temperatures of 200, 220 and 240°C, respectively. The relationship between absolute temperature and moisture diffusivities obtained from the baking data was modeled using an Arrhenius type equation. The activation energy was determined to be 25.7 kJ/mol.

RÉSUMÉ

Les changements au niveau du transfert de masse (perte d'humidité et absorption d'huile), de la couleur, et de la texture des croquettes de poulets ont été étudiés pour comparer les effets de deux modes de cuisson: à l'huile à haute température et au four. La cuisson à l'huile à haute température a été effectuée à trois températures différentes: 150, 170 et 190°C. Les durées de friture ont varié de 1, 2, 3 à 4 minutes. Le traitement au four a été effectué à trois températures différentes: 200, 220, et 240°C, avec des temps de traitement de 10, 15, 20 et 25 minutes.

La teneur en eau du panage des pépites de poulet frites a diminué suivant une courbe de séchage typique variant de 0.90 à 0.22 g/g (dB), alors que celle du cœur des pépites a régressé presque linéairement de 1,96 à 1,4 g/g (dB). Les teneurs en graisse du panage et du cœur ont augmenté linéairement avec le temps. En général, la température de friture a affecté de manière significative la teneur en eau du panage et du cœur. Cela a également affecté la teneur en graisse du noyau mais pas de celle du panage. La teneur en eau du panage des pépites cuites au four a diminué de 0,90 à 0,18 g/g (dB) pareillement aux échantillons frits. D'un autre côté, celle du cœur des pépites n'a pas change excepté aux phases avancées du traitement au four (de 2 à 0,87 g/g (dB)). La teneur en eau du panage et du cœur a diminué de manière significative avec une température de cuisson plus élevée.

Lors de la friture à haute température, les paramètres de légèreté (L) et de couleur jaune (b) ont diminué avec le temps et la hausse de la température, alors que le paramètre de rougeur (a) s'accentuait. Durant le traitement au four, les paramètres de

légèreté et de couleur jaune ont augmenté puis diminué avec le temps de cuisson. L'effet de la température de cuisson était significatif.

Des essais de résistance à la perforation ont été réalisés sur les pépites de poulet cuites. La charge maximale supportée par les échantillons témoins était de 0,6 N. Lors de la friture la résistance a augmenté jusqu'à atteindre 6,1 N. Elle a atteint 7,36 N lorsque les pépites ont été cuites au four. L'effet du temps et de la température de cuisson s'est avéré significatif sur les valeurs de charge maximale pour les deux traitements. Ces valeurs ont augmenté de manière significative avec le temps de cuisson et avec des températures de cuisson plus élevées.

En supposant une géometrie infinie et mince, et en utilisant une des solution à la deuxième loi de Fick.s de la diffusion, la perte d'humidité du panage des pépites de poulet a été modelisée. Les paramètres modèles obtenus ont été employés pour calculer la diffusion de l'humidité. Dans le cas de la friture graisse la diffusion de l'humidité étaient de 2,1, 2,9 et 2.5 x 10^{-9} m^2/s pour des températures de friture de 150, 170 et de 190°C. Tandis que les diffusions de d'humidité obtenues en cas de cuisson au four étaient 1,9, 2,3 et 3,16 x 10^{-10} m^2/s pour les températures de cuisson de 200, 220 et de 240°C, respectivement. Le rapport entre la température absolue et les diffusions de l'humidité obtenues à partir des données de traitement au four a été modélisé en utilisant une équation de type d'Arrhenius. L'énergie d'activation a été déterminée pour être 25,7 kJ/mol.

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It would take another whole thesis, a lifetime, and still won't be adequate!

I'll start by dedicating this work to them.

To my Mom and Dad,

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CHAPTER I

INTRODUCTION

1.1. Deep Fat Frying

Deep fat frying is one of the most common methods of cooking. It is widely used in chain fast food restaurants as well as at the household level. Deep fat frying yields desirable characteristics such as crispness, appealing flavor and color in foods in a relatively short cooking time. This explains the popularity of fried food products such as French fries, potato chips, donuts, extruded snacks, fish sticks and chicken nuggets.

Deep fat frying (or immersion frying) is a process where the food product is immersed in hot oil bath for a certain period of time. Oil temperatures are usually kept above the boiling point of water, hence frying results in moisture loss from the food product by evaporation. This moisture loss is accompanied by oil uptake from the frying medium.

Typically deep fat frying results in the formation of crust at the surface of the food due to the fast evaporation of water from the peripheral parts of the food. The crust is one of the characteristics that gives fried foods their desirable texture.

1.2. BREADED FOOD PRODUCTS

Breaded fried food products are widely consumed in restaurant chains and in various homes. The wide variety of battered and breaded foods includes cheese, fish, fruits, meat, poultry, seafood and vegetables. The per capita consumption of this category of foods has grown from less than 5 lb in 1982 to 15 lb in 1992 in the USA. Batters and breadings comprise 30% of such foods by weight. Thus the consumption of batters and breadings is estimated at 1.143 billion lb per year in the USA (Shukla, 1993). The combined consumption of batters and breadings in Europe, Japan, Oceania, and the other Pacific Rim countries is estimated to be about 2 billion lb (4.4 billion kg). More recent statistics from the USDA Economic Research Service, showed that poultry products have been the only meat products witnessing an increase in demand by the consumers during the last three decades (Haley, 2001). The per capita consumption of poultry meat in the USA had increased two-fold from 34 lbs (15.4 kg) in 1970 to 68 lbs (30.8 kg) in the year 2000. Chicken nuggets and chicken strips topped the list as the most popular poultry products in the recent years. Similar trends in consumer preference for poultry meats were observed in Canada as well. The per capita consumption of poultry meats had increased from 28 kg in 1991 to 35 kg in year 2000 (Statistics Canada, 2001).

Chicken nuggets are one of the most popular types of breaded food products. Chicken nuggets are coated with a batter-breading layer that acts as a barrier to moisture loss in addition to carrying spices and other ingredients for flavor enhancement. This coating layer renders chicken nuggets apart from other fried products such as French fries.

The chicken nuggets available to consumers are typically par-fried or partially fried. They could then be finish-cooked by several methods, including deep fat frying, oven baking, and microwave cooking. It was suggested that deep fat frying results in better quality of prepared nuggets compared to other preparation methods (Yoon et al., 1999). General guidelines for final preparation of chicken nuggets are usually provided by the product manufacturers. Nevertheless, very little research has been done to objectively understand the process of deep fat frying of chicken nuggets.

1.3. Frying Oils and Health Concerns

Recent trends toward healthy eating habits have created consumer driven pressures to produce foods with lower fat content. Nevertheless, fat is a superior source of energy at 9 kcal/g (more than double the caloric values of proteins and carbohydrates) and is essential as a component of cell structure. Dietary fats, such as frying oils, provide fatty acids and fat-soluble vitamins.

There are many types of oils and fats available for frying. These mainly include vegetable oils such as canola oil and soybean oil, palm oils including palm oil and coconut oil, and animal fats such as butter and tallow. In general fats are from animal origin while oils are from plant origin. Currently, the food industry uses blends of animal/vegetable fats and partially hydrogenated vegetable oils (Brooks, 1991). During deep fat frying, oils undergo chemical and physical alterations. Moisture from the food and atmospheric oxygen cause oxidative alterations, while high temperatures cause thermal alterations. The oil could be contaminated with food ingredients. Changes that take place in frying oils during heating at high temperatures retard their quality. These changes include increasing viscosity, decreasing heat capacity and lowering smoking point. Long use of frying oils results in the formation of free fatty acids, free radicals, and other volatile compounds (Blumenthal, 1991; White, 1991). These compounds impose hazard to human health. However, it was suggested that the physical deterioration of frying oils precedes the dangerous chemical degradation (Walter and Serbia, 1991). Foods fried in degraded oil are typically of low quality with off-flavor taste. Hence, the consumption of foods prepared with overused fats is a self-limiting process. Therefore, dietary hazards due to over consumption of fats are the major problem to be addressed in deep fat fried foods. Cardiovascular diseases, obesity and diabetes are all health complications associated with dietary fat intake. The National Heart, Lung and Blood Institute (NHLBI) recommends that caloric intake from all fat sources to be limited to 30% of total caloric intake (Perkins and Erikson, 1996). Hence the importance of understanding fat uptake in deep fat fried products.

In spite of all the health concerns associated with dietary fat, fried products remain popular. This is due to the unique textural and quality attributes imparted by deep fat frying. Hence, more emphasis is placed on finding ways to reduce oil uptake during frying. Also, alternative cooking methods that will produce similar textural and sensory characteristics are being explored. Oven baking is often suggested as an alternative in finish-cooking of par-fried food products such as chicken nuggets.

1.4. Objectives

The main objectives of this study were to determine the influence of various cooking parameters on quantitative and qualitative textural and mass transfer characteristics of chicken nuggets during deep fat frying and oven baking. The specific objectives were:

1. Determine moisture loss and fat absorption in chicken nuggets during deep fat frying and during convection oven baking at different temperatures.
2. Estimate and mathematically model moisture diffusivities in deep fat fried and oven baked chicken nuggets.
3. Evaluate the color and textural properties of deep fat fried and oven baked chicken nuggets cooked at different temperatures and times;
4. Compare the kinetics of changes in mass transfer and textural characteristics of chicken nuggets cooked using deep fat frying and oven baking.

CHAPTER II

LITERATURE REVIEW

Literature about deep fat frying is abundant; nevertheless, little work has been published on deep fat frying of chicken nuggets despite their wide consumption. As a breaded product, chicken nuggets have unique characteristics due to the presence of a significant batter-breading coating at the outer surface. Several researchers worked on deep fat frying of breaded or coated foods (Hale and Goodwin, 1968; Lane et al., 1980; Rao and Delaney, 1995; Rayner et al., 2000), however it was rarely the case where chicken nuggets were the products under investigation during deep fat frying (Yoon et al., 1999). The lack of published research on deep fat frying of chicken nuggets might be attributed to the complexity of the composite structure of chicken nuggets as well as the fact that most food companies conduct their own research according to their needs.

2.1. Batters and Breadings

2.1.1. Definitions

Breading of food products is believed to improve desirable properties of these foods. It enhances the texture, appearance and flavor of food. It acts as a barrier against moisture loss thus retaining the juicy properties desired in meat products like chicken, besides serving as a carrier of seasoning and spices. It was noted that the literature uses different terminologies in studying "breaded" food products. The terms "breading", "batter" and "coating" are used, thus defining the meaning of each of these terms is necessary. Suderman (1983) defined a batter as "a liquid mixture comprised of water, flour, starch, and seasonings into which food products are dipped prior to cooking". Breading was referred to, as " a dry mixture of flour, starch and seasonings, coarse in nature, and applied to moistened or battered food products prior to cooking", while a coating was defined as " the batter and/or breading adhering to the food product after cooking".

2.1.2. Classification of batters and breadings

Breadings can be broadly classified according to their cereal origin, with wheat and corn being the most commonly used cereal grains in the breading industry. Breadings could also be classified according to their functionality. Suderman (1993) referred to "free flowing breading" and "non free flowing". A free flowing breading flows from the hand after a person holding makes a fist, which is referred to as "hand test". If the breading packs in the fist then it is considered non-free flowing.

Batters could be classified as "conventional", "traditional" and "leavened" batters (also called tempura). Table 2.1 from Suderman (1986) provides more details on classification of batters and breadings.

2.1.3. Composition of batters and breadings

The manufacturers of batter mixes have been relying on intuition for determining the proper ingredients of batter coatings. Thus a scientific understanding of the mechanisms and properties governing the qualities of batter systems is still lacking.

Table 2.1. Classification of batters and breadings

Category	Classification	Type
Breadings	Cereal grain-base	Wheat flour-based Corn flour-based Other flour based

	Functionality	Free flowing
		    Fine
		    Medium
		    Course
		    Bakeable
		Non free-flowing

	Specialty	Seasoned or Flavored Green bread crumb Potato flakes Cereals Cracker crumbs Dry Sauces Predusts

Batters	Conventional (unleavened)	Wheat flour-based
		Corn flour-based
		Starch based
		    Modified
		    Unmodified
		Traditional
		    Egg and milk based

	Tempura (leavened)	(May include all conventional batters, with leavening agents)

Source: Suderman (1986).

Batter formulations usually constitute of major and optional ingredients. Flour, which is finely ground starchy material like corn, rice, soy and/or barley, constitutes the major ingredient of batters. No exact recipes are defined for batter systems, thus, depending on the food material and the desired coating properties, batter systems can be very flexible to allow for development of food products. Batter recipes are formulated to account for subsequent processing such as freezing and reconstitution during cooking. Table 2.2 provides a general idea on typical formulations of batter mixes (Loewe, 1993).

Table 2.2. Typical ingredients of batter mixes

Ingredient	% Range
Major ingredient	
Wheat flour	30-50
Corn flour	30-50
Sodium Bicarbonate	Up to 3
Acid phosphate	Adjust based on neutralizing value
Optional ingredients	
Flours from rice, soy, barley	0-5
Oil shortening	0-10
Dairy powders	0-3
Starches	0-5
Gums, emulsifiers, colors	Less than 1
Salt	Up to 5
Sugars, dextrins	0-3
Flavorings, seasonings, breadings	Open

Source: Loewe (1993)

2.1.4. Coating functions

Batters are typically used with a complementary breading layer. Breading coatings are mainly starch containing, thus providing a base for crust formation, especially in foods low in starch content such as meets and vegetables. The breading-induced crust is responsible for the retained moisture content in the fried product, which subsequently results in lower oil uptake (Rao and Delaney, 1995). The breading layer adds granulation properties to the food, and it enhances color, flavor and crispness of the final product. Batter coatings usually serve as an adhesion layer between the food surface and the breading. Desirability of the breaded product is determined by the uniformity and thickness of the coating, which relates to batter viscosity. A higher viscosity batter will result in higher pick up of breading than will a thin watery batter (Loewe, 1993). At the restaurant level, batter coatings are usually provided as dry mix to which water is added, as for retail chains, battered foods are prepared in large quantities, packaged, and frozen.

2.1.5. Coating Characteristics

Major characteristics of coatings in breaded food products are the appearance, color, flavor and crispness. Appearance is the most primary concern when consuming battered and breaded products. Color and overall appearance are largely affected by the amount of coating adhering to the food. Suderman and Cunningham (1977) reported that appearance and coating uniformity were better on fresh chicken parts than on frozen and thawed parts. Hanson and Fletcher (1963) found that thickening agents could affect the coating appearance. Thicker coatings produced smooth surfaces, while thinner coatings allowed bubbles to appear on the surface of the food.

The color of prepared breaded products is another important aspect of the coating "appearance". Color development in coatings is a function of breading ingredients, cooking method, and cooking oil. Ingredient composition plays an important role in determining the extent of Maillard reactions, hence protein and sugar contents are important factors influencing color development (Suderman, 1983). Hanson and Fletcher (1963) observed apparent color differences due to various ingredients. Landes and Blackshear (1971) found coating color to be dependent on oil type. They reported that soybean oil yielded better color of fried chicken pieces than peanut oil.

Crispness is an important coating characteristic. This texture attribute is a desirable quality in breaded food products. Hanson and Fletcher (1963) studied the role of thickening agents in affecting coating crispness and texture. They suggested that mixtures of thickening agents provide optimum crispness characteristics. Hale and Goodwin (1968) found that precooking improves texture and toughness of the battered chicken pieces. Rao and Delaney (1995) reported that breading of chicken pieces had a more crispy texture when fried at atmospheric pressure as compared to pressure frying.

Flavor was studied as one of the factors affecting the desirability of coatings. Hale and Goodwin (1968) found that flavor was affected by cooking method. Deep fat frying was found to yield a significantly better flavor than microwave cooking followed by deep fat frying.

2.1.6. Cooking methods

Breaded food products are popular for their desirable qualities as well as for the convenience they provide in terms of preparation methods. Most breaded products could be prepared by deep fat frying or oven baking, as well as by microwave heating. Each of these methods has its advantages and disadvantages. Deep fat frying is a relatively fast method of cooking that endorses the product with desirable characteristics such as flavor, color, and crispness. However, oil uptake that occurs during deep fat frying is a concern to health. Oven baking is another cooking method that could be used for preparing breaded food products. The main disadvantage of this method is that it requires longer cooking times. Microwave cooking is a very fast way of preparing breaded foods, however the end product will lack in terms of color, texture and flavor.

Yoon et al. (1999) studied deep fat frying of chicken nuggets and beef steak fingers in comparison to two other preparation methods namely oven cooking and hot-air frying. Both products had higher moisture content when hot air fried than when deep fat fried. For chicken nuggets, both, hot air frying and oven cooking resulted in lower fat content than deep fat frying. While for beefsteak fingers the fat content was not significantly affected by the method of cooking. Sensory testing conducted by the authors showed that most panelists preferred the deep fat fried products over baked or hot-air fried ones for flavor, crispness, mouth feel, and overall likeability of the product.

Loewe (1993) suggested that the optimal way of cooking breaded food products is by deep fat frying at temperatures ranging between 177-204°C. The rapid heat transfer will quickly set the coating structure thus limiting the time for moisture loss, which is removed in exchange with oil uptake during the frying process. As a matter of fact frying is the method adopted for cooking coated foods, particularly chicken nuggets, in most popular food service chains. Oven heating is another method for cooking breaded products used usually in house holds. This process yields a moderately acceptable product in terms of crispiness, color and flavor. Indeed, to attain better quality attributes by oven cooking, oil is added to the dry coating mix. This helps in obtaining fried-like appearance and flavor.

Microwave heating is another alternative fast cooking procedure for breaded foods. Microwave oscillations induce molecular vibrations that result in frictional heating of the food, and the resultant product is characteristically mushy with minimal crispiness especially at the breading layer (Loewe, 1993). Thus microwave treatment of final product doesn't yield the desirable properties typically expected from breaded products. Loewe (1993) also described important coating characteristics like appearance, color, crispness and flavor. The most acceptable and desired characteristics are obtained by using deep fat frying for breaded products. Frying yields a greater degree of browning than conventional oven baking or microwave cooking where browning is extremely difficult. Flavor is dependent on the recipe and on the method, time and temperature of cooking. Here too the most desirable results are obtained by deep fat frying.

Hale and Goodwin (1968) studied the effects of different pre-cooking procedures before deep fat frying of breaded chicken pieces. In their first trial two cooking methods were used; deep fat frying for 14 minutes at 152°C and deep fat frying for 4 minutes at 177°C preceded by 4 minute of microwave precooking. The authors found that the microwave pre-cooked breast pieces had lower shear values than the deep fried breast pieces. This difference in shear values may be attributed to the fact that deep fat frying method tended to dehydrate the muscle tissue of the breast more than the method where microwave cooking was used. The moisture content was significantly lower for the deep fat fried pieces in both the muscle tissue and the batter complex. The fat content was not affected by cooking method. Although there was a 3 percent difference it was insignificant. The authors noted that blood extrusion was observed in the pre-micro waved pieces, which proved to be detracting by the panelists.

In their second trial of Hale and Goodwin (1968) three cooking methods were tested: Deep fat frying for 15 minutes at 153°C, deep fat frying for 5 minutes at 182°C preceded by 5 minutes of microwave pre-cooking, and deep fat frying for 5 minutes at 182°C preceded by 10 minutes in autoclave. The pre-autoclaved deep fat frying methods produced significantly lower shear values for the thigh than did deep fat frying alone. The three cooking methods showed significant differences in moisture content, which was compensated for by difference in fat content. Thus the final yield values were essentially the same.

Lane et al. (1980) noted the rapid growth of breaded chicken market between the 60's and 70's. From 3.7 million pounds of breading produced in 1961 up to 75 million pounds in 1973. Much of the increase was a result of growing franchise frying and serving of chicken. The authors tried to correlate internal temperature with minimum sensory doneness and to obtain frying time-temperature relationships that correspond to minimum doneness in breaded deep fried chicken thighs. Chicken thighs were fried at 163°C up till various end point temperatures ranging from 82-99°C. Internal temperature of 93°C was established as the minimum end-point temperature corresponding to doneness. The range of thigh weights used was between 98 and 137 g, and since heat penetration is faster for lower weight thighs, then a higher endpoint temperature is required to attain similar doneness level. Heat penetration was more rapid at initial phases, then it approaches zero at around 93-95°C of internal temperature after 15-16 minutes. The time required to reach 93°C endpoint at frying temp of 163°C was 14.5 minutes.

2.2. Deep Fat Frying

Deep fat frying is a process where food products are cooked and dried by immersion in hot oil for a specific period of time. The frying oil is usually kept at temperatures above the boiling point of water (between 150°C and 190°C), hence the cooking process starts right after the food is immersed into the oil. The frying process involves rapid changes in the physical, chemical and sensory characteristics of the food. During frying, starch is gelatinized, tissues are softened, and enzymes are partially inactivated.

2.2.1. Heat Transfer

The heat transfer occurring during deep fat frying follows two distinctive modes: conduction and convection. Conductive heat transfer takes place within the food material itself under unsteady state conditions (Singh, 1995). The rate of heat transfer is affected by the thermal properties of the food such as thermal conductivity, thermal diffusivity, specific heat and density; however the values of these properties change during the frying process (Buhri and Singh, 1994).

Heat transfer by convection takes place between the frying oil and the food product. The convective heat transfer coefficient is the major determinant of the heat transfer rate between the frying medium and the food; it relates the property of a boundary layer energy transport from one side of a body or medium to another. The temperature gradient existing between the food product and the frying medium is another determinant of the convective heat transfer. The mathematical model for convective heat transfer is Newton's Law:

$$Q = hA(T_\infty - T_s) \tag{2.1}$$

Where, h is the convective heat transfer coefficient,

A is the surface of contact between product and oil

T_∞ is the oil temperature

T_s is the food product temperature

The heat transfer coefficient is greatly influenced by the complicated interactions at the food-oil interface. These interactions are mainly due to the bubbling caused by the evaporation of water from the food product to the oil (Singh, 1995).

Farkas et al. (1996) observed that, during frying, the temperature within the fried food is restricted to the boiling point of water due to the presence of moisture. Only after the removal of the moisture does the temperature exceed the boiling point. Farkas suggested four distinct stages during the frying process: initial heating by convection, where the product rises from its initial temperature and approaches the boiling point of water; surface boiling stage which is signaled by the bubbling process and beginning of the crust formation at the food surface; followed by a falling rate stage where most of the moisture loss takes place but at a decreasing rate, and where several physiochemical changes occur as well as further crust formation; then the bubble end point which is witnessed after considerable frying time due to the diminishing moisture removal rate.

In breaded food products heat is transferred from the oil to the food passing through the breading layer. The temperature starts to rise and a portion of the water present in the breading is converted into steam, which in turn is driven to the food surface. Oil uptake starts as frying time passes and as the food coating becomes more permeable to fat penetration while the moisture release to the food surface diminishes (Suderman, 1993). According to Suderman (1993) heat transfer is higher in breadings as a porous material, partly because of the greater thermal conductivity of oil present in the breading.

2.2.2. Mass transfer

Moisture loss and oil uptake are two major mass transport phenomena that take place during deep fat frying. This mass transfer mechanism is coupled to the heat transfer process. During frying, heat causes the loss of the moisture from food by evaporative cooling and subsequent oil uptake takes place.

One of the fundamental approaches in describing mass transfer during deep fat frying has been to assume that oil uptake and moisture loss are diffusion controlled. Hence Fick's Law of Diffusion would be the governing equation for mass transfer:

The mass transfer process taking place during deep fat frying is a function of frying time and temperature. Gupta et al. (2000) reported that moisture content of French fries decreased with time for all frying temperatures. The instantaneous rate of moisture loss at any time was proportional to the moisture content at that instant. Oil uptake and moisture removal increased with frying temperature.

Bauman and Escher (1995) reported that drying or moisture removal was accelerated at higher oil temperatures during deep fat frying of potato chips.

In an extensive study on deep fat frying of French fries, Krokida et al. (2001a) reported a significant decrease in moisture content during frying. Moisture content was negatively affected by oil temperature, and for a fixed frying temperature, moisture decreased with frying time.

Gamble et al. (1987) described the mechanisms of oil uptake and moisture loss during frying. They suggested that the moisture loss takes place due to the diffusion gradient between the dry surface and wet core of the food, and the pressure gradient created by the evaporation of the inner moisture. However, for the steam to escape through the food it has to find "selective weaknesses" in the food structure. Hence enforcing the food structure would reduce moisture loss and eventually reduce oil uptake. This principle might find its way in explaining moisture loss and oil uptake during frying of breaded products such as chicken nuggets where the batter/breading systems provide a protective and reinforcing coating for the food material. Both, oil uptake and moisture loss schemes were found to be closely correlated to the square root of frying time (Gamble et al., 1987). Moisture content was reported to follow a typical drying profile. Rapid initial drop in moisture was followed by a continuous drying period. The drying rate then decreases below 20% moisture. The authors visually observed a continuous decrease in bubbling intensity during frying.

Several studies correlate moisture loss with frying time and it was suggested that moisture loss is proportional to the square root of frying time (Mittelman et al., 1982; Ashkenazi et al., 1984; Gamble et al., 1987; Rice and Gamble, 1989).

Rice and Gamble (1989) described moisture loss during deep fat frying as a mass transfer process governed mainly by the driving force of moisture removal and resistance to that removal:

$$\text{Rate of mass transfer} = \text{Driving force/Resistance} \qquad (2.2)$$

The authors used Fick's law of diffusion in one dimension to predict moisture diffusion coefficients during frying. The diffusivity values were constant for frying times between 1 and 4 minutes, however these values undergo a sudden change as frying time approaches 6 minutes. This was attributed to the non-homogeneous property of the food material (1.5 mm thick potato slices).

Ni and Datta (1999) found that moisture content decreases with oil temperature, and increases significantly with initial moisture because both surface evaporation and subsequent internal evaporation are higher for foods with higher moisture.

Blumental (1991) used a water soaked sponge to simulate the coupled heat and mass transfer mechanisms in deep fat frying. The author describes how the water migrates from the internal parts of the product to the surface due to the dehydration effect of frying. The moisture is lost by evaporative cooling as it reaches the surface where the oil is at temperature levels above boiling point of water. As moisture is migrating outward, an opposite inflow of oil starts to take place as the oil moves in by mass diffusion to fill up the cavities created after moisture loss.

2.2.3. Modeling of deep fat frying

Despite the wide spread use of deep fat frying, this processing method is still not fully understood due to the complexity of the various parameters involved. The frying process is a coupled heat and mass transfer process where heat transfer could be described as the driving force for the mass transfer mechanism.

Frying could be seen as a high temperature drying process taking place in a liquid fat medium (Costa and Oliviera, 1999). Food products are immersed in the frying medium where heating starts to take place. Consequently, water is evaporated and lost by the bubbling mechanism observed at the surface of the food. A dry crust is formed, then fat absorption into the voids created by the release of water vapor takes place (Ufheil and Escher, 1996; Gamble and Rice, 1987). Thus, predicting moisture loss during deep fat frying is a key to understanding and modeling the frying process.

Moisture loss was often assumed to be controlled by internal diffusion based on mass transfer theory (Farkas et al., 1996; Rice and Gamble, 1989). Farkas et al. (1996) modeled moisture loss during frying of an infinite slab. The authors defined two spatial regions of interest; the crust and the core. Several possible mechanisms for liquid transport were suggested in the core region; however, only one theory was tested. It was proposed that mass transfer in the core region occurs by diffusion due to a concentration gradient based on Fick's second law of diffusion. The authors assumed constant diffusivity. As for moisture loss in the crust region, the authors suggest that it is limited to the flux of water vapor through the crust layer to the surface. It was proposed that this water vapor flux was driven by a pressure gradient from the core/crust interface to the surface.

Other researchers modeled moisture loss in deep fat frying using the first term of the solution to the diffusion equation (Kozempel et al., 1991; Moriera et al. 1991). Kozempel et al. (1991) conducted frying experiments at 185, 195, and 201°C using French fries. The authors proposed that the diffusivity was a function of oil temperature and an Arrhenius type relationship was suggested between diffusivity and oil temperature. Using experimental data for oil temperature and product moisture content, the effective diffusivity was found.

Moreira et al. (1991) followed a similar approach in predicting moisture diffusivity in tortilla chips. A one-term approximation of Crank's (1975) solution to Fick's second law of diffusion was utilized. The one-term exponential model was used to describe moisture loss as well as oil content of fried tortilla chips.

2.3. Factors Influencing Oil Uptake During Deep Fat Frying

Oil uptake could be singled out as the most important aspect of deep fat frying due to health concerns. Many factors play a role in affecting the mechanism of oil uptake; some of these factors are discussed hereafter.

2.3.1. Frying time

Frying time is an important factor in influencing oil uptake. Fat content of fried products was found to increase significantly with frying time (Krokida et al., 2001a). Ni and Datta (1999) reported that oil uptake is initially high, and then slows down to become linear with time during deep fat frying of potatoes. The initial high rate of oil uptake was attributed to the large difference in oil concentration between the surrounding oil and the initial oil concentration in the food.

Table 2.3. Effect of frying time on oil uptake in French fries*

Frying Temp (°C)	Frying Time (s)	Moisture Content (% wb)	Oil Content (% wb)	OC/MR**
182	120	58.7	9.6	0.33
182	135	50.0	12.1	0.24
182	150	46.2	13.9	0.24
182	165	44.5	15.7	0.25

*Initial moisture content = 70% (wb, par-fried)
**OC/MR: Oil content / Moisture removal
Source: Zak and Holt (1973)

Zak and Holt (1973) studied oil uptake during deep fat frying of French fries. They reported increasing oil content and decreasing moisture with frying time at a constant temperature of 182°C (Table 2.3).

Du Pont et al. (1992) reported that oil content increased by almost 50% during the first 4 min of frying of frozen French fries. The fat content remained constant between 4 and 6 min, and then it increases after 9 min of frying. The authors also reported constant moisture content between 4 and 6 min of frying, which indicates that the process enters a steady state condition at that stage of frying.

2.3.2. Post-frying Oil uptake

Several researchers suggested that the major portion of oil uptake occurs during the cooling stage after frying. During cooling, the decreasing internal temperature of the fried product will induce a drop in internal pressure, which will act as a driving force for the absorption of the oil still covering the surface of the food.

Ufheil and Escher (1996) studied oil uptake during deep fat frying of potato slices. They introduced a fat-soluble and heat stable dye into the oil at different times before the end of frying in order to determine the dynamics of oil uptake throughout the process. The authors concluded that oil does not penetrate the potato slices during frying, but it is taken up by the potato slice after it is removed from the oil bath. The oil uptake mechanism was considered to be a function of the equilibrium between adhesion and drainage of oil after removing the samples from the frying medium.

Gamble and Rice (1987) drew similar conclusions. They reported that fat absorption occurs when potato slices are removed from the frying oil. The cooling effect will create a pressure drop inside the product and oil will eventually fill up the voids created by the moisture loss.

2.3.3. Frying temperature

The effect of frying temperature on oil uptake during deep fat frying is still a subject of controversy. Bauman and Escher (1995) found that final oil content was lower at higher oil temperatures due to a shorter residence time of the food in the frying oil.

Diaz et al. (1999) reported that temperature had little effect on fat content during frying of plantain while moisture content was greatly affected by oil temperature and frying time. Other authors reported higher oil uptake with increasing frying temperatures (Gamble et al., 1987; Kassama and Ngadi, 2000; Bauman and Escher, 1995). Gamble et al. (1987) suggested that the oil content is not directly related to frying temperature itself, but more intimately associated with the final moisture content, which in turn is affected by temperature. It was also suggested that higher oil temperatures cause a faster crust formation, which facilitates the process of oil absorption (Moreira et al., 1999), but this could be ruled out by shorter frying time.

2.3.4. Moisture content

Moisture content of deep fat fried foods is an important factor in determining oil uptake. Most fried food materials are high in moisture content. During frying, moisture loss creates cavities or pores as well as passageways in the food. These cavities are known as capillary pores and through them the oil penetrates during frying. Several authors correlated fat absorption and moisture loss; a linear relationship was reported throughout deep fat frying between oil uptake and moisture loss (Gamble et al., 1987; Krokida, 2000). Costa and Oliveira (1999) suggested that predicting water loss is critical for modeling and controlling deep fat frying of potatoes.

2.3.5. Oil properties

Oil is primarily the medium of heat transfer in deep fat frying; hence oil properties play a vital role in affecting the frying process. Successive use of frying oil induces changes in physical and thermal oil properties such as viscosity, surface tension, specific heat, and convective heat transfer coefficient. These changes can prolong the frying time and increase the total amount of oil in the product (Moreira et al., 1999).

Viscosity is one of the oil properties associated with fat uptake during frying. It could be defined as the internal friction within a fluid, or its resistance to flow. Vegetable oils are generally considered to be Newtonian fluids, that is they exhibit a linear relationship between shear stress and shear rate according to the following equation:

$$\sigma = \mu\dot{\gamma} \tag{2.3}$$

Where σ is the shear stress, $\dot{\gamma}$ is the shear rate and μ is the viscosity.

Oil viscosity is affected by temperature during frying. Table 2.4 (Tseng et al., 1996) shows the change in viscosity of soybean oil under the effect of temperature.

Table 2.4. Temperature effect on the viscosity of soybean oil

Temperature (^{o}C)	Viscosity (Pa.s)
25	0.0532
50	0.0222
90	0.0081
120	0.0049
150	0.0031
190	0.0020

Source: Tseng et al. (1996).

As a Newtonian fluid, vegetable oil viscosity decreases with increasing temperature, which might facilitate the process of oil uptake. However, as degradation of frying oil increases, its viscosity will increase (Tseng et al., 1996).

Thermal properties of oil such as specific heat (C_p) and convective heat transfer coefficient (h) play an important role in the effectiveness of oil as a frying medium. Specific heat of corn oil was found to decrease significantly (by 14%) upon long use due to high levels of degradation (Tseng et al., 1996). The convective heat transfer coefficient (h) was found to decrease nonlinearly with degradation time in soybean oil. With up to 30 hours of frying, the change in h values didn't decrease significantly; however after 30 hours of frying a sharper change in h values was observed and these values were significant.

As for Oil type, this factor seems to have no significant effect on either moisture loss or oil uptake (Krokida et al., 2001a).

2.3.6. *Oil-food surface tension*

Pinthus and Saguy (1994) studied the effect of surface tension between oil and food during deep fat frying of potato cylinders. Samples dipped in emulsifiers for 20 seconds showed a significantly lower oil uptake after frying compared to un-dipped samples. The lower oil uptake was due to the lower oil-food surface tension due to the interference of the emulsifiers at the food surface. Moreira and Barrufet (1998) arrived to similar findings. They reported higher oil content with higher oil-product interfacial tension during frying of tortilla chips. The authors noted that the final oil content is dramatically affected by the initial moisture content of the product, however, most of the oil uptake occurred during the cooling stage following frying. Moreira and Barrufet (1998) examined oil absorption during cooling. They suggested a correlation between air temperature and oil uptake during cooling. Lower air temperatures resulted in higher oil uptake. That was attributed to a more intense pressure drop within the product's pore spaces, and thus more oil absorption from the surface.

2.3.7. *Product geometry*

Product size and thickness have their effect on the process of deep fat frying, particularly on fat absorption. Gamble and Rice (1988) reported that increasing the thickness of fried potato slices reduces their percent fat content. The volume of oil expressed as a percentage of the total volume of the slice was found to decrease from 25.2 % for 0.88 mm thickness to 14.8% for 1.58 mm thickness. However, the total volume of fat absorbed was found to increase with larger thickness due to the increase of the surface area available for oil uptake. The authors concluded that oil uptake increases with higher surface to mass ratio of fried foods.

The decrease in oil content associated with increasing thickness of potato slices was reported to be nonlinear (Bauman and Escher, 1995). The oil content was found to increase significantly more between 0.8 and 1.1 mm thickness as compared to between 1.3 and 1.6 mm thickness.

2.3.8. Specific gravity of food

Specific gravity of fried foods is one of the properties that affect oil uptake during deep fat frying. High specific gravity of raw potatoes produces potato chips with lower oil content (Lulai and Orr, 1979). A decreasing linear relationship was reported between oil content of potato chips and specific gravity of raw potatoes.

French fries exhibited similar pattern of oil uptake with varying dry matter content (Lesinska and Leszczynski, 1989). French fries made from potatoes with 24% dry matter had 9% less oil than French fries made form varieties with 19.5% dry matter.

2.3.9. Pre-frying treatment

Pre-frying treatments such as drying, osmotic dehydration, blanching and partial cooking such as baking and microwave heating were studied to determine their effect on deep fat fried foods.

Krokida et al. (2001b) studied the effect of pre-drying on moisture loss and oil uptake during frying of French fries. Samples were pre-dried for different times then fried till they reach equilibrium moisture content. The equilibrium moisture content decreased with longer pre-drying time. As for the oil uptake, the authors found that pre-drying decreased the oil uptake of French fries during frying. Pre-drying of French fries slows down the transport mechanism of both oil and moisture during deep fat frying. Final oil content ranged from 0.1 to 0.2 kg/kg on dry basis.

The same authors (Krokida et al., 2001c) studied the influence of osmotic dehydration pre-treatment on moisture loss and oil uptake in French fries. Osmotic dehydration decreased the initial moisture content of the French fries. The moisture content for the same frying time was found to decrease with osmotic dehydration pretreatment. Oil content was also affected. Osmotic dehydration caused a reduction in the final oil content after frying.

Gupta et al. (2000) studied the effects of oil temperature and duration of pre-drying time on the kinetics of moisture removal, oil uptake and quality of French fries. The authors reported that moisture content decreased with time for all frying temperatures. The instantaneous rate of moisture loss at any time was proportional to the moisture content at that instant. Oil uptake and moisture removal increased with frying temp.

The effect of blanching prior to frying on oil uptake was studied by Lamberg et al. (1990) in combination with different drying conditions. Oil content was highest for potatoes that were blanched without drying as compared to samples blanched and dried at 80°C for 5 min under various relative humidity values.

Other pre-frying treatments that influence oil uptake of fried products are baking and microwave heating. Moreira et al. (1997) studied the effect of baking time on the final oil content of tortilla chips fried for 60 seconds. The final oil content was found to decrease significantly with baking and with increasing baking time.

2.4. Moisture Loss and Fat Uptake During Frying of Breaded Foods

In breaded food products, oil absorption and moisture loss are affected by breading porosity and density (Suderman, 1993). Porous breading particles absorb oil and lose moisture during frying faster than do dense breadings.

Mostert and Stadelman (1964) reported that breading increased fat absorption when cooked by methods where fat is used. Pressure deep fat frying and oven frying produced significantly higher moisture content than did conventional deep fat frying or pan-frying. Fat content was highest in pan fan frying than in any other cooking method tested

Rayner *et al.* (2000) used soy protein isolate solution to develop a coating for deep fried foods (donuts, potato disks and French fries). The coating was evaluated for reducing oil uptake during frying, and there was a significant fat reduction of 55% on dry basis between fried uncoated and coated donuts. The change in moisture content was reported insignificant between the coated and uncoated fried samples

2.5. Sensory Characteristics of Fried Products

2.5.1. Crust formation and textural changes

A crispy crust is one of the unique and desirable characteristics of deep fat fried foods. The crust is formed at the surface of the food during frying. The intimate interaction between the frying medium and the food surface will result in rapid moisture loss and other physiochemical reactions that will result in crust formation.

Ngadi et al. (1997) modeled moisture transfer during deep fat frying of chicken drum. The authors identified a region of rapidly decreasing moisture content at the surface of the chicken drum. That region starts on the surface at the onset of frying then it extends into the inner parts of the drum. This mechanism results in the formation of a dry surface layer that could be identified as the crust, which is one of the characteristic properties of fried foods.

Ateba and Mittal (1994) worked on the dynamics of crust formation and crust firmness during deep fat frying of meatballs. The authors used the Instron (universal testing machine) and a penetration test was conducted on samples cut in half using a 3 mm diameter probe. The penetration depth was 10 mm and the penetration rate was 200 mm/min. Ateba and Mittal compared force histories for different frying times during the penetration tests. The average of four replicate histories was taken. The authors observed an increase in peak force with frying time. The peak force values reached as high as 3N for frying time of 540 sec; this increase in firmness was explained by the crust formation and heat denaturation of the protein.

Krokida et al. (2001) investigated texture, which is one of the most important characteristics of fried products. The crispness of the food material was defined as the ratio of maximum stress to maximum strain. The authors reported that maximum stress and maximum strain increased during frying and as the frying temperature decreases, while crispness decreased with higher oil temperatures.

Rao and Delaney (1995) studied frying of breaded chicken pieces. They compared post-frying breading texture in pressure frying versus atmospheric frying, and they reported that the breading had a more crispy texture when fried at atmospheric pressure, while pressure frying yielded a softer breading with higher moisture content. Rao and Delaney stated that scanning electron micrographs showed a more continuous structure of starch in atmospheric pressure frying. Rao and Delaney observed that pressure-frying results in softer texture while frying at atmospheric pressure yields a crispy texture. Using a stereo pycnometer, the respective volumes of samples were reported and the corresponding bulk densities were: 1.28 g/cm^3 for pressure frying and 1.17 g/cm^3 for atmospheric frying. This fact was used by the authors to explain the crispier breading under atmospheric pressure frying, where an open network of starch and protein is formed. That network has very little moisture (free evaporation) and is mostly filled with air and oil. And hence the product is crisp in contrast to the breading of pressure-fried product.

Rayner *et al.* (2000) compared the texture of deep fat fried potato disks coated with soy protein isolate solution verses uncoated samples. The authors used the Universal Testing Machine (Instron) to perform a puncture test on potato disks by a 3.1 mm diameter plunger and the maximum force during penetration was recorded. The rate used was 1 cm/s using a 50 N load cell. The plunger was pressed through the sample to a depth of 1.2 cm (half way through the potato disks which were 2.5 cm thick). The coated samples showed softer textural properties as compared to uncoated samples. The authors attributed that to the formation of softer crust when coating the samples.

2.5.2. Color

Color is one of the most important characteristics of deep fat fried foods. Krokida et al. (2001a) investigated the effect of frying conditions on the color of fried products. They measured the values of L (lightness), a (redness), and b (yellowness) of the potato strips. Lightness (L) increased in the early stages of frying then it remained constant in later stages. Oil temperature had a negative effect on the lightness of the fried potatoes. Samples with smaller thickness values had lower lightness for same frying time. Parameter a or redness, which is undesirable in French fries, increased with frying temp. Parameter b, or yellowness, also increased with temperature increment. The authors noted that lower oil temp (less than 170^{o}C) gave less redness and more yellowness to the fried product.

Ateba and Mittal (1994) studied the kinetics of crust color during deep fat frying of meatballs. The authors used spectrum analyzer to determine the lightness (L), redness (a) and yellowness (b) of the samples. The "L" value measured lightness ranging from zero (black) to 100 (white), the "a" value measured redness ranging from +60 to –60 and the "b" value measured yellowness ranging from + 60 to –60. A decrease in lightness was observed with frying time, this was attributed to the Maillard browning reaction during frying of the meatballs. Moisture loss during crust formation and the increased temperature accelerated the Maillard browning at the surface of the meatballs. The authors reported a decrease in "a" (redness value) and "b" (yellowness value). This decrease was explained by the denaturation of meat pigments.

Suderman (1993) mentioned that browning of fried breaded products is affected mainly by frying time and the presence of reducing sugars. So frying times can be reduced when sugar levels are increased. However, there are some foods that require long frying times, such as breaded chicken parts; for these, breadings with less reducing sugars should be used in order to keep a desirable color in the end product.

Krokida et al. (2001b) investigated the effect of pre-drying treatment on color of French fries using the Lab color measuring system. The drying process decreased the lightness, L, value of the potato strips, however it increased upon frying to values ranging between 40 and 50. Parameter "a", which is an indicator of redness, increases significantly during drying due to browning reactions. Frying increases the "a" value even further, which is not a desirable color in French fries. As for parameter "b" (includes yellowness), it decreases during the pre-drying process due to browning, and this is considered a negative effect since yellowness is a desired color in French fries. All in all, the authors found that pre-drying causes color deterioration in French fries due to the browning effect. In another study conducted by the same authors (Krokida et al., 2001c), The effect of osmotic dehydration on the color of French fries was studied. Lightness "L" and yellowness "b" were found to decrease with osmotic dehydration, while the redness, or "a" parameter increased significantly. The authors attributed this increase in redness to the browning reactions that took place during frying of samples that underwent osmotic dehydration, especially when sugar based solutions are used in the process.

2.6. Oven Baking As an Alternative To Deep Fat Frying

Oven baking is one of the commonly used cooking methods as an alternative to deep fat frying. As oven baking doesn't involve liquid fat as cooking medium, it is considered a "healthier" cooking method as far as increase in fat content is concerned. The resulting baked product might be of a slightly inferior quality in terms of texture and flavor as compared with the same product undergoing deep fat frying (Yoon et al., 1999; Loewe, 1993).

2.6.1. Comparing oven baking with deep fat frying

Fundamentally, oven baking and deep fat frying can both be described as high temperature drying processes where coupled heat and mass transfer mechanisms take place. However, the media and intensities of heat transfer set the two cooking methods apart. Considering convection oven baking, air is the heating medium, as opposed to oil in the case of deep fat frying. As air has a much lower heat capacity than liquid fats, the intensity of cooking would be much lower during baking than during deep fat frying. Thus more time is required to attain the same level of cooking in the case of oven baking. As a matter of fact, the temperatures used in oven baking are usually higher than temperatures employed during deep fat frying. Oven baking temperatures typically range between 200 and 240°C while deep fat frying takes place at oil temperatures ranging from 150 to 190°C.

As far as mass transfer is concerned, both oven baking and deep fat frying involve moisture loss as a major transfer phenomenon. However, in the case of deep fat frying, oil uptake is another significant mass transfer phenomenon that doesn't exist in baking operations.

2.6.2. Modeling the oven baking process

Oven baking is one of the important unit operations in the food industry, and its importance is more pronounced as an alternative to deep fat frying where fat content is a health concern. The properties of baked products are naturally influenced by the process parameters, thus optimizing these parameters is necessary to obtain a final product with desirable characteristics. From here comes the importance of modeling and quantitatively understanding the heat and mass transfer mechanisms taking place during oven baking.

Generally, researchers modelled heat and moisture transfer during baking as a surface evaporation process. Internal moisture transfer was assumed to take place by diffusion from the inner portions of the products towards the surface where the moisture is lost under the effect of the latent heat of evaporation. This approach was used to study baking of meatballs (Huang and Mittal, 1995), meat patties (Chen and Marks, 1997) and roast meat (Singh et al., 1984). Thus the importance of predicting moisture diffusivities in food products during oven baking is emphasized.

Fick's second law of diffusion, or one of it is simplifications, is often used as the governing equation for mass transfer during drying of food materials as in the case of baking. One of the simplified forms of Fick's second law assumes an infinite slab shape with one-dimensional moisture diffusion and constant diffusivity value. With such assumptions Fick's law takes the following form:

$$\frac{\delta M}{\delta t} = D\frac{\delta^2 M}{\delta x^2} \qquad (2.4)$$

where D is the diffusivity, x is the plate thickness

with the following initial and boundary conditions:

$M(x,0) = M_{o,}$ uniform initial moisture content

$M(x_o,t) = M_{e,}$ final moisture content at the product surface

With the above assumptions and initial and boundary conditions, the solution to equation 1 found in Crank (1975) would be:

$$M_r = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2 Dt}{L^2}\right] \qquad (2.5)$$

Where $M_r = (M - M_e)/(M_o - M_e)$; M is average moisture content at time t (kg/kg d.b.), M_o is initial moisture content, and M_e is equilibrium moisture content, D is moisture diffusivity (m^2/s), t is time in seconds, and L is plate thickness (m)

However this solution could be approximated using a one term exponential model where one term of the infinite series is used (Moreira et al., 1991; Zogzas and Maroulis, 1996). Thus the final equation takes the following form:

$$M_r = \frac{8}{\pi^2}\exp(-kt) \qquad (2.6)$$

CHAPTER III

MATERIALS AND METHODS

3.1. The Chicken Nugget Samples

Most of the chicken nugget products available to consumers in the local grocery stores come partially fried (par-fried) by the manufacturer. Commercial, par-fried and frozen chicken nuggets were purchased from a major local manufacturer. The average weight of the slab shaped chicken nuggets was 21 g with thickness of 12 mm, length of 50 mm and width of 40 mm (Figure 3.1).

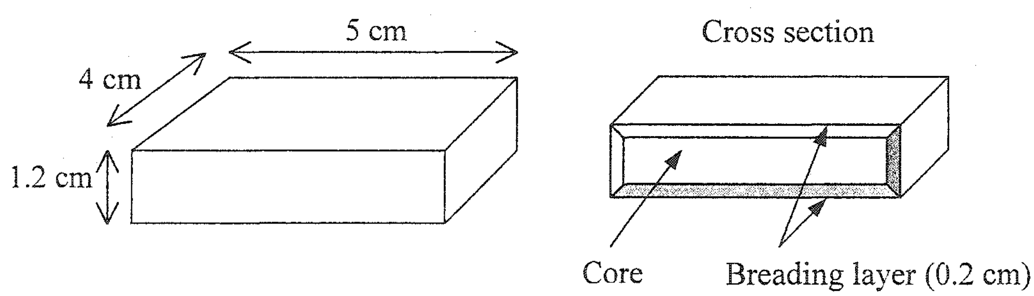

Figure 3.1. Schematic drawing representing the shape and dimensions of the chicken nuggets.

The supplier of the chicken nuggets agreed to provide a list of the ingredients of the chicken nuggets but not the specific formulations as that was considered proprietary information. Table 3.1 includes the ingredients of the chicken nuggets used in this experiment

Table 3.1. The ingredients of the chicken nuggets used in this study

Component	Ingredients
Meat core	Chicken breast meat Modified wheat flour Spices and rosemary extract
Pre-breading	Toasted wheat crumbs
Batter	Corn flour, corn starch, wheat flour, Salt, dextrose, guar gum.
Breading	Toasted wheat crumbs (Wheat flour, partially hydrogenated soybean oil, salt, dextrose, and yeast and spices)

The chicken nuggets were par-fried by the manufacturer in hydrogenated canola and/or Soya vegetable oil.

3.2. Cooking and Analysis

The chicken nugget samples were stored in a freezer at –18°C until the time of frying. Before frying, the chicken nuggets were removed form the freezer, placed in well-sealed Ziploc bags and thawed for 30 min in a warm water bath at about 50°C until completely and uniformly defrosted.

3.2.1. Frying

An industrial deep fat fryer was used (Computron 7000, Henny Penny Corp., Eaton, Ohio). The fryer had a capacity of about 15 liters. With 4 nuggets fried in every run (21 g each nugget), the ratio of oil mass to fried product mass was high enough to eliminate any changes in temperature of the oil upon the onset of frying. Hydrogenated vegetable oil was used in all the frying runs (Liquid Frying Shortening, CanAmera Foods®, Oakville, ON).

In this experiment the chicken nuggets were fried at three levels of oil temperature namely 150, 170, and 190°C. For each temperature level the samples were fried for 4 different intervals of time, namely 1, 2, 3 and 4 min. Each chicken nugget was considered as an individual sample and four samples were fried simultaneously in every frying run. During frying the chicken nuggets were separately placed in wire baskets so as to trace each nugget individually throughout frying. The baskets were immersed to a depth of 10 cm in the frying oil. After frying the nuggets were allowed to drain then they were blotted gently with dry tissue paper to remove any excess oil on the surface. The temperature of the frying oil was monitored. It was controlled at ± 2°C off the set temperature.

3.2.2. Oven baking

Baking was performed in a convection oven (Isotemp 700, Fisher Scientific, Pittsburgh, PA). Chicken nuggets were placed individually in metal wire baskets in order to insure uniform convection heating from all side of the nuggets. Three samples were baked at a time, during which they were placed in the center of the oven while baking. All the baked samples were placed in the same location in the oven. Three baking temperatures were used namely 200, 220 and 240°C. Four baking times namely 10, 15, 20 and 25 min were adopted. The temperature of the oven was monitored throughout the baking runs and it was within $\pm 1^{o}C$ off the set temperatures.

3.2.3. Separation of breading and core portions

After cooking the breading and core portions of the chicken nuggets were separated before any further analysis. The breading/batter coating was carefully detached from the core portion of the chicken nuggets. This process proved to be fairly simple and precise as the breading pealed off discretely from the chicken nugget surface. The breading and core parts were then placed in different aluminum cans for further analysis. The breading and core portions were analyzed for moisture and fat contents.

3.2.4. Moisture loss

Moisture content was determined using the AOAC standard method (39.1.02). The separated portions of the chicken nuggets were weighed then dried to a constant weight in a convection oven (Isotemp 700, Fisher Scientific, Pittsburgh, PA). Drying took place for about 18 hours at a temperature of $102^{o}C$. The samples were placed in a dessicator to cool down, then weighed, and the moisture was determined by difference in weight. The moisture content was reported on a dry weight basis.

3.2.5. Fat extraction

The Soxhlet method was used for fat analysis (AOAC standard). The convection oven dried chicken nugget portions were ground uniformly using a homogenizer-blender (Proctor-Silex, model E160B, Picton, ON). Fat extraction was performed with petroleum ether, using a solvent extractor (SER148, Velp Scientifica, Usmate, Italy).

3.2.6. Textural analysis

A Universal Testing Machine (INSTRON) was used to determine the crispness of the cooked chicken nuggets. A puncture test using a 5.1 mm cylindrical probe and a 50 kN load cell was performed. The probe was allowed to penetrate throughout the thickness of the chicken nuggets at a head velocity of 300 mm/min and the force values were recorded at a rate of 5 readings per second. Two punctures, 1 cm apart, were performed on the central portion of each chicken nugget. All the samples were tested within 10 min after cooking, which is reasonably within the time it takes for serving fried chicken nuggets in food service chains or at household levels. The maximum load values were recorded for each baking time/temperature combination in both fried and baked nuggets.

3.2.7. Color determination

The color of the cooked chicken nuggets was determined using a chroma meter (Minolta CR 300, Minolta Camera Co. Ltd., Osaka Japan). L, a, and b color indices were used. The L parameter is a measure of lightness ranging from zero to

100 (zero for black, 100 for white). The a parameter is a measure of greenness/redness ranging from –60 (at the most green end of the scope) and +60 (at the most red end of the scope) and the b parameter is a measure of blueness/yellowness ranging form –60 (blue) to +60 (yellow).

Four replicates of fried chicken nuggets were evaluated for every temperature/time frying combination. Two color readings were taken from each chicken nugget sample and the average was considered as a composite reading. The values for each of the three color parameters (L, a, and b) were recorded and analyzed separately. One way Analysis of Variance was performed and Duncan's multiple range mean separation was used.

3.3. Statistical Methods

The SAS System software (Version 8, 1999, SAS institute Inc., Cary, NC, USA) was used for statistical analysis on a Windows 98® platform. All the results were analyzed using two-way analysis of variance to determine the effect of the different temperatures and times used for both deep fat frying and oven baking. Statistical significance was determined at the 5% significant level. Duncan's Multiple Range mean separation was performed where the ANOVA procedure showed significance.

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Moisture Loss and Oil Absorption During Deep Fat Frying

The separated breading and core portions of the deep fat fried chicken nuggets were analyzed for moisture and fat contents as described in Chapter 3. Two-way analysis of variance was conducted to determine the effect of frying time and temperature on moisture and fat contents. ANOVA procedure was also performed on the data obtained from the different treatments of frying time and temperature. The ANOVA tables are presented in Appendices I and II.

4.1.1. Moisture Loss in breading

The ANOVA procedure (Appendix I-A) showed that the main effect of temperature on the breading moisture was significant ($p<0.05$). Breading moisture decreased significantly with higher frying temperature. The influence of the different treatments of frying time and temperature also significantly (at the 5% level) influenced moisture content of the breading portion of chicken nuggets during deep fat frying. Mean separation was performed using Duncan's multiple range test (Table 4.1). The breading moisture decreased at all frying temperatures following a peculiar drying behavior as shown in Figure 4.1.

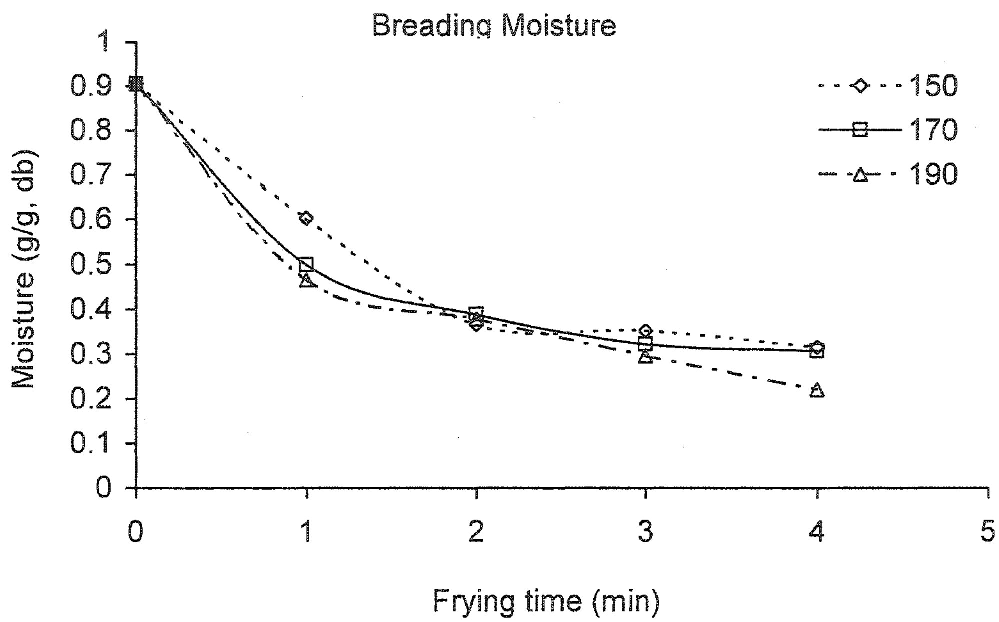

Figure 4.1. Average moisture content of the breading portion of chicken nuggets during frying at 150, 170 and 190°C.

Table 4.1. Mean values for breading and core moisture contents at different frying temperatures and times.

Frying Temp. (°C)	Frying time (min)	Breading Moisture g/g db	Core moisture g/g db
Control	Control	0.90 A*	1.96 A*
150	1	0.60 B	1.98 A
	2	0.37 E F	1.75 C
	3	0.35 F	1.71 C D
	4	0.32 G	1.61 G F
170	1	0.50 C	1.87 B
	2	0.39 E	1.69 C D E
	3	0.32 G	1.63 G F E
	4	0.31 G	1.57 G H
190	1	0.47 D	1.85 B
	2	0.38 E F	1.66 D F E
	3	0.30 G	1.52 H
	4	0.22 H	1.40 I

*Means with the same letter are not significantly different (Using Duncan's Multiple range test at alpha level = 0.05)

The drying curve exhibited an initial constant drying rate period lasting for 1 min followed by a dropping rate period between 1 and 2 min, then a second constant rate period from 2 to 4 min of frying. The second constant rate period showed a lower drying rate than the initial constant rate period. This moisture loss pattern was directly associated with the composite structure of the chicken nuggets. The initial constant-rate drying stage observed during the first minute of frying was due to the rapid moisture loss from the breading portion. The second constant-rate drying stage witnessed between 2 and 4 min of frying was due to the onset of moisture loss from the core portion of the chicken nuggets. This moisture transferred from the core had to pass across the breading layer. Thus the breading moisture content was affected by the moisture lost from the core at the later stages of frying.

The mean values of moisture content of the breading portion of chicken nuggets decreased from 0.90 g/g for control samples to 0.22 g/g for fried samples (at 190°C for 4 min). All treatments of frying temperature and time resulted in significantly lower moisture content as compared to the control.

For 150°C, frying time had significant effect on breading moisture content except between 2 and 3 min where moisture content was not significantly different ($p<0.05$). For 170°C, moisture content decreased significantly with frying time until it reached a level of about 0.32 g/g after 3 min, which was not significantly different from the moisture at 4 min (0.31 g/g). For 190°C, moisture content decreased significantly with every min of frying to reach a low of 0.22 g/g after 4 min.

Krokida et al. (2001) obtained similar patterns of moisture loss during deep fat frying of 10 mm thick potato strips. The authors used potato strips with initial moisture content ranging from 0.6 to 1 kg/kg on dry basis and similar moisture loss patterns were obtained. Gamble et al. (1987) also reported similar decrease in moisture content upon frying of potato chips at 145, 165 and 185°C for 5 min. The final moisture content was dependent on temperature, as it was lower for higher frying temperatures. The moisture content of potato chips obtained by Gamble et al. (1987) during frying at 145°C ranged from 66.5% (wb) at 1 min of frying to 14.7% after 5 min of frying. The higher the temperature of frying the lower the moisture contents obtained for same frying times. Moreira et al. (1997) obtained similar results during deep fat frying of tortilla chips.

Indira et al. (1999) studied moisture loss of samosa, a deep fat fried product constituting of a dough casing stuffed with mashed potatoes and spices. The moisture loss from the casing was monitored at frying temperatures of 155, 170 and 185°C. The moisture content of the casing followed similar patterns as these observed in the breading portion of the chicken nuggets in this study. Moisture decreased with frying time and temperature following a typical drying behavior. The initial moisture content of the samosa casing was 0.5 g/g (on dry basis). Upon frying the moisture dropped to about 0.2 g/g after 10 min of frying then it did not change after that. The same pattern was observed for all the frying temperatures.

4.1.2. Moisture loss in core

The effects of frying time and temperature on moisture content in the core portion of the chicken nuggets were shown to be significant ($p<0.05$) (Appendix I-B). Moisture content in the core portion of the chicken nuggets decreased significantly with increasing frying time and temperature. The moisture content in the core region of the chicken nuggets decreased almost linearly with frying time for all the frying temperatures as shown in Figure 4.2. The mean values of moisture content of the core part of the chicken nuggets ranged from 1.98 g/g (150°C for 1 min) to 1.4 g/g (190°C for 4 min).

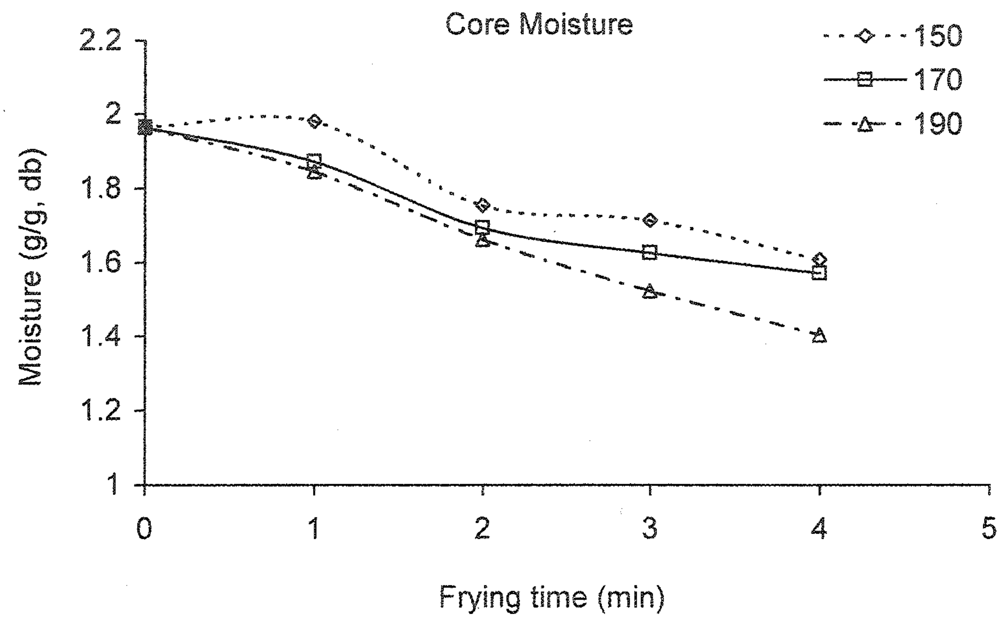

Figure 4.2. Average moisture content of the core portion of chicken nuggets during frying at 150, 170 and 190°C.

At 150°C, the moisture content of the core portion was not significantly different from the control after 1 min of frying. Meat moisture decreased significantly after 2 min, then it was not significantly different between 2 and 3 min, but again significantly decreased at 4 min. At 170°C, core moisture content of the fried samples was significantly lower than that of the control. Core portions of nuggets fried for 1 min retained significantly higher moisture content as compared to longer frying times. At 190°C, every frying minute resulted in significantly lower moisture content in the meat portion.

The moisture content in the core part of the chicken nugget decreased with frying time at a lower rate than the moisture content of the breading. This low rate of moisture loss might be due to the protective coating provided by the batter and breading layer surrounding the core, and also due to the intrinsic difference in the properties of the core material. The moisture loss behavior from the core region follows almost a linear trend. This indicates a constant rate of drying, which resembles the early constant drying rate observed in the breading layer. The drying behavior of the core is expected to exhibit a dropping rate stage upon further frying time. The results obtained for moisture loss from the core portions of chicken nuggets are comparable with the rates of moisture loss observed by Zak and Holt (1973) on French fries. The authors reported a linear decrease in moisture content of samples fried at 182°C for 3 min.

The initially slow loss of moisture from the core portions of the chicken nuggets in this study was similar to what was reported by Indira et al. (1999). The authors reported no change in moisture content of the stuffing portion of fried samosa samples. The stuffing moisture content remained at about 63% (wb) throughout frying regardless of frying temperature. The unchanged moisture content of the stuffing portion of the samosa was attributed to the protective and sealing function of the casing, which is comparable with the role of breading/batter portion of chicken nuggets in retarding moisture loss form the core.

Some of the breading/batter ingredients such as wheat flour, corn flour, and guar gum provide a structured layer that surrounds the core portion of the chicken nugget; hence reducing moisture loss. This protective function of batter/breading coatings was emphasized by Suderman (1983) and by Davis (1983).

4.1.3. Oil uptake in breading

The fat content of the breading portion increased significantly with time. The breading portion seemed to absorb more of the frying oil with longer residence time in the fryer regardless of the frying temperature. This could be attributed to the porous structure of the breading, which constitutes mainly of breadcrumbs. Such highly porous structure might have facilitated the transport of oil and moisture simultaneously; thus the oil absorption started taking place right upon the onset of frying.

The fat content of breading portion of non-fried chicken nuggets used in this study was 0.35 g/g on dry basis. The fat contents of breading portions of fried chicken nuggets ranged from 0.35 to 0.42 g/g (Figure 4.3 and Table 4.2).

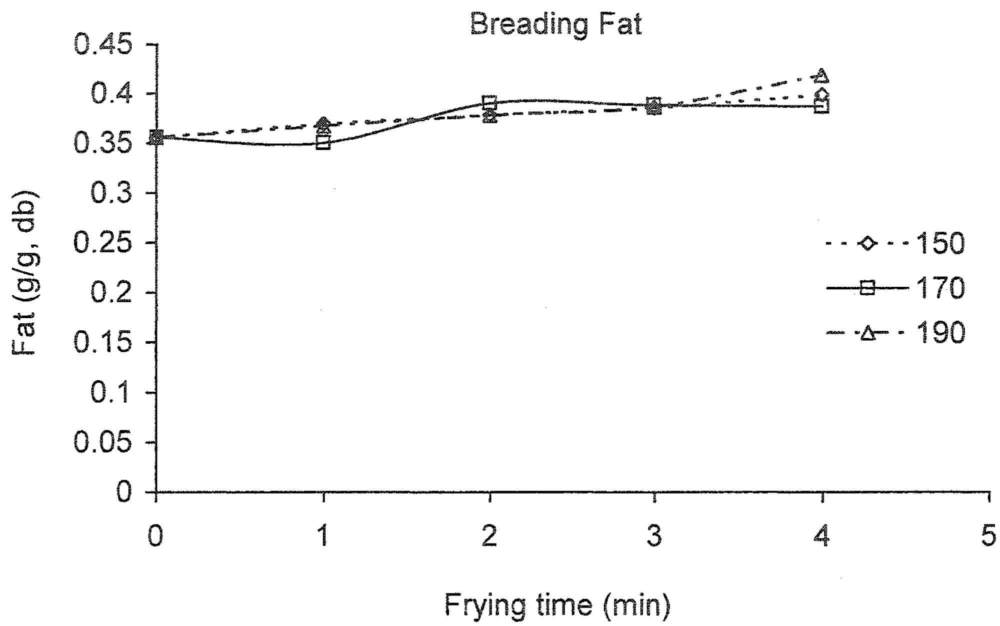

Figure 4.3. Average fat content of the breading portion of chicken nuggets during frying at 150, 170 and 190°C.

All combinations of frying time and temperature resulted in significantly higher breading fat content as compared to the control, except for frying at 170°C for 1 min. For 150°C, the breading fat content was significantly higher than the control for all frying times. However, the fat content of the breading did not change significantly with frying time except after 4 min of frying when it became significantly higher. For 170°C, the fat content of the breading increased significantly after 2 min of frying then it was steady at around 0.39 g/g. For 190°C, breading fat content did not change significantly during the initial 2 min of frying, however it was significantly higher after 4 min.

Table 4.2. Mean values for breading and core fat contents at different frying temperatures and times.

Frying Temp. (°C)	Frying time (min)	Breading Fat g/g db	Core Fat g/g db
Control	Control	0.35 A*	0.31 A*
150	1	0.37 B	0.31 A
	2	0.38 B C	0.35 C D
	3	0.39 C D	0.35 C D
	4	0.40 D	0.34 C D
170	1	0.35 A	0.34 B C
	2	0.39 C D	0.35 C D
	3	0.39 C D	0.37 E
	4	0.39 C D	0.38 E
190	1	0.37 B	0.33 B
	2	0.38 B C	0.35 C D
	3	0.39 C D	0.35 D
	4	0.42 E	0.38 E

*Means with the same letter are not significantly different (Using Duncan's Multiple range test at alpha level = 0.05)

In a similar study on deep fat frying of samosa, Indira et al. (1999) reported rapid oil uptake by the samosa casing during the first 2 min of frying as oil content increased from an initial 10 % (db) db to about 16-19 % (db) after 2 min. Upon further frying (from 2 min to 12 min), Indira et al. (1999) reported a linear increase in fat content of the casing portion of the samosa. After 12 min of frying the oil contents of the samosa casing ranged from 17 to 21 % (db) depending on frying temperature. The oil uptake trend observed by Indira et al. (1999) in the casing portion of samosa and during the last 10 min of frying was similar to that reported in the breading portion of the chicken nuggets in this study.

4.1.4. Oil uptake in core

Frying temperature had a significant effect ($p<0.05$) on the fat content of the core portions of fried chicken nuggets. The fat content was significantly higher at 170 and 190°C than at 150°C, with no difference between fat contents at 170 and 190°C.

The mean fat content of the core portion ranged from 0.31 g/g (150°C for 1 min) to 0.38 g/g (170°C for 4 min) while the initial core fat content of the control was 0.31 g/g (Figure 4.4 and Table 4.2). All combinations of frying times and temperatures resulted in significantly higher core fat content when compared to the control, except for frying at 150°C for 1 min. At 150°C, the core fat content increased significantly between 1 and 2 min of frying, then it did not change significantly. At 170°C and for the first 2 min of frying the core fat content did not increase significantly, but it did increase significantly after 3 and 4 min.

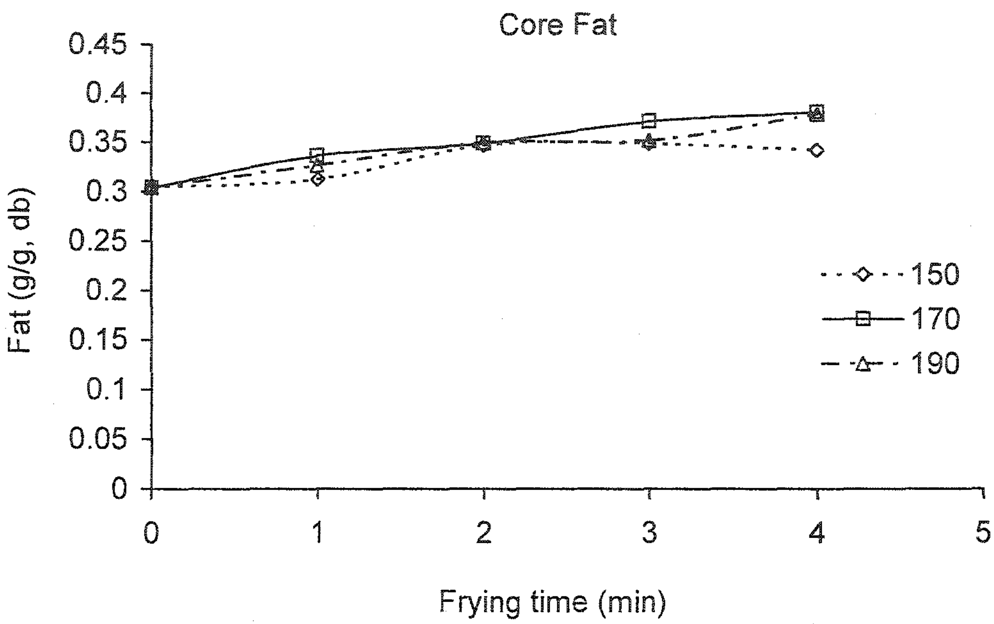

Figure 4.4. Average fat content of the core portion of chicken nuggets during frying at 150, 170 and 190°C.

At 190°C, fat content after 2 to 3 min was significantly higher than after 1 min. Frying for 4 min also resulted in significant increase in core moisture content.

The significant effect of temperature on oil uptake by the core portion of the chicken nuggets could be related to the moisture loss behavior from the core. A linear correlation was suggested to exist between oil uptake and moisture loss in deep fat fried foods (Gamble et al., 1987; Krokida, 2000). During deep fat frying moisture loss creates cavities that are subsequently occupied by the absorbed oil. In the previous sections of this Chapter, frying temperature was shown to have significant effect on moisture loss from the core. Thus, the fat uptake was affected by frying temperature.

Other authors reported higher oil uptake with increasing frying temperatures (Gamble et al. 1987, Kassama and Ngadi, 2000, Bauman and Escher, 1995). However, Gamble et al. (1987) stated that, generally, oil content is not directly related to frying temperature itself, but more closely associated with the final moisture content, which, in turn, is affected by temperature.

The behavior of oil uptake upon frying in this study was found to be similar to that witnessed during late stages of frying performed on French fries (Zak and Holt, 1973). However, in the case of a composite food such as samosa, Indira et al. (1999) reported no increase in fat content of the core stuffing portion of the product during deep fat frying. The reported initial fat content was 2% on wet basis, and it did not change throughout frying regardless of frying temperature. Furthermore, Indira et al. (1999) reported no change in moisture content in the internal stuffing portion of samosa upon frying, which may explain the unchanged oil content of the stuffing.

4.2. Moisture Loss and Oil Absorption During Oven Baking

The separated breading and core portions of the oven baked chicken nuggets were analyzed for moisture and fat as described in Chapter 3. Analysis of variance was conducted to determine the main effect of baking temperature on moisture and fat contents. ANOVA procedure was also performed on the data obtained from the different treatments of baking time and temperature. The ANOVA tables are presented in Appendix II

4.2.1. Moisture Loss in breading

The main effect of baking temperature was significant on the moisture content of the breading portions of the chicken nuggets (Appendix II-A). Higher baking temperatures resulted in significantly lower moisture content in the breading.

Moisture loss from the breading portion followed a pattern similar to the one observed in the case of deep fat frying (Figure 4.5). A constant drying rate stage was observed during the first 10 min followed by a dropping rate stage from 10 to 15 min. Then, between 15 and 25 min of baking, a second constant rate stage was observed. The second constant rate was due to the onset of moisture loss from the core portion of the chicken nuggets. Moisture loss from the core portion started after 10 to 15 min of baking, and the moisture lost had to pass through the breading layer.

Hence, moisture interfered with the drying pattern of the breading and created the second constant drying stage.

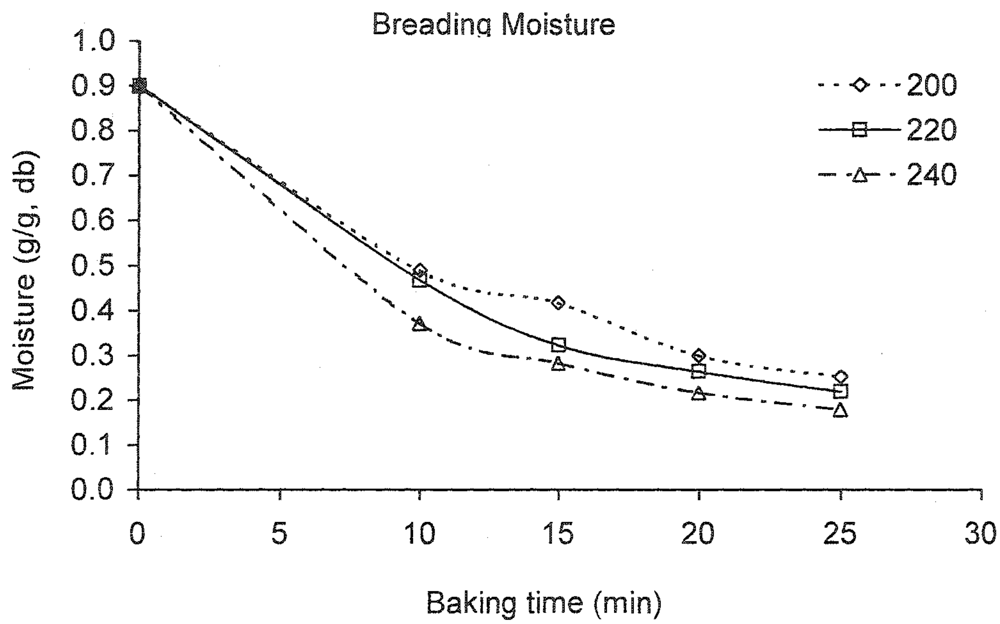

Figure 4.5. Average moisture content of the breading portion of chicken nuggets during oven baking at 200, 220 and 240°C.

The breading moisture content of baked nuggets ranged from 0.49 g/g (200°C for 10 min) to 0.18 g/g (240°C for 25 min) while the initial moisture content in the control samples was 0.90 g/g. The ANOVA procedure showed high significance among the means of breading moisture for the temperature and time parameters used (Appendix II-A). Mean separation was performed and presented in Table 4.3.

Table 4.3. Mean values for breading and core moisture contents at different baking temperatures and times.

Baking Temperature (°C)	Baking time (min)	Breading Moisture g/g db	Core moisture g/g db
Control	Control	0.90 A*	1.99 A*
200	10	0.49 B	2.04 A
	15	0.42 C	2.04 A
	20	0.30 E F	1.97 A B
	25	0.25 G	1.75 C
220	10	0.47 B	2.02 A
	15	0.32 E	1.90 B
	20	0.26 G	1.76 C
	25	0.22 H	1.24 D
240	10	0.37 D	2.00 A
	15	0.28 F G	1.77 C
	20	0.22 H	1.74 C
	25	0.18 I	0.87 E

*Means with the same letter are not significantly different (Using Duncan's Multiple range test at alpha level = 0.05)

At 200°C baking temperature, the breading moisture decreased significantly with every 5 min of baking to reach a low of 0.25 g/g after 25 min. Similar trend was observed at the baking temperature of 220°C as at 200°C. The lowest moisture content obtained at 200°C was about 0.22 g/g after 25 min of baking. At the baking temperature of 240°C, the moisture content was reduced to about 0.18 g/g after 25 min, which was the lowest value obtained for all baking temperature and time combination.

4.2.2. Moisture loss in core

Baking temperature had a significant effect on the moisture content of the core portions of the chicken nuggets (Appendix II-B). Higher baking temperatures yielded significantly lower moisture contents in the core portions of the chicken nuggets.

The trend of moisture loss from the core portion of the baked chicken nuggets was different from the pattern observed in the breading (Figure 4.6). It took at least 10 min of baking for the moisture content to start changing. This was verified statistically as shown in Table 4.3.

At 200°C baking temperature, the core moisture content did not change significantly during the first 20 minutes of baking, then it dropped significantly after 25 min to 1.75 g/g. For 220°C baking temperature, the core moisture content decreased significantly with baking time and reached a low of 1.24 g/g after 25 min. As for 240°C baking temperature, the core moisture was significantly lower at 15 min than at 10 min; then it was not significantly different at 20 min, but it dropped sharply and significantly to 0.87 g/g upon 25 min of baking.

Moisture loss from the core portion started taking place after 10 min of baking for all baking temperatures (Figure 4.6). The drying rate increased gradually between 10 and 15 min of baking.

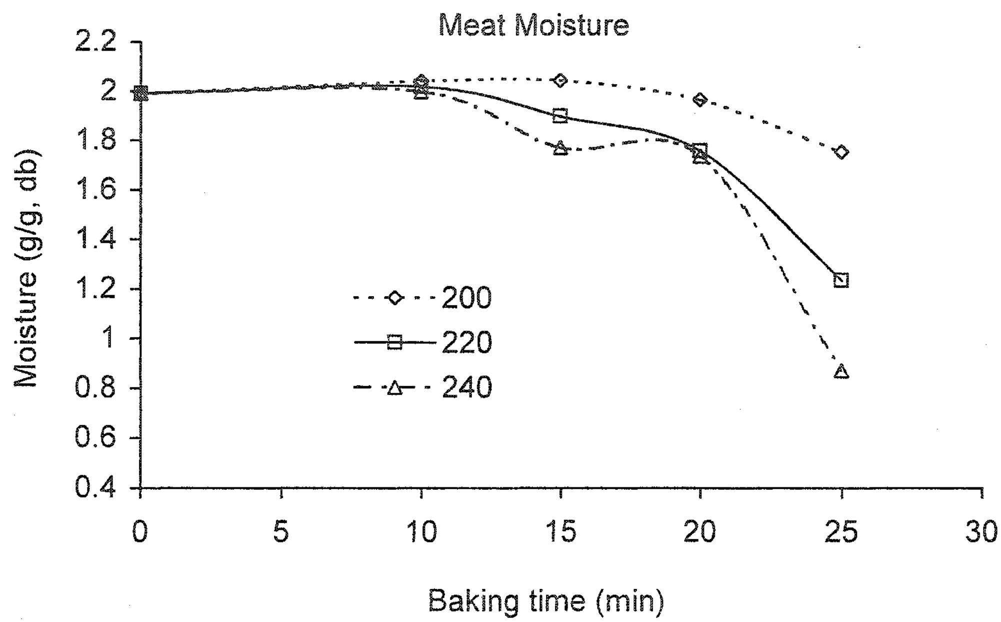

Figure 4.6. Average moisture content of the core portion of chicken nuggets during oven baking at 200, 220 and 240°C.

The region between 10 and 20 min of baking resembles the “settling stage” experienced at the onset of certain drying processes. During the settling down period, the surface conditions of the product come into equilibrium with the drying air. If we assume that the breading layer represents the “surface boundary” of the core portions, then the settling down period is the time it takes the breading moisture to approach equilibrium with the drying air. That was why the settling period took such a relatively long time, while it is often a negligible proportion of the drying cycle (Brennan et al. 1981). The moisture loss pattern then enters a constant rate drying phase that starts after 20 min of baking and lasts till the end of the baking process.

The pattern of moisture loss from the core portion of baked chicken nuggets was different from the result obtained for frying. The moisture content in the core portion of fried chicken nuggets started decreasing upon the onset of frying, while in the case of baking it did not change during the first 10 min. This was mainly due to the difference in the intensity of heat transfer between the two cooking methods. Heat transfer, which is the driving force behind moisture loss, is much higher in the case of deep fat frying than in oven baking. Frying oil, which is the heat transfer medium possesses a much higher heat capacity than air, which is the heat transfer medium in oven baking.

There was no significant change in the fat content of both the breading and core portions of the chicken nuggets within the baking time and temperature frames used in this experiment (Figures 4.7 and 4.8 and Appendix II-C and II-D). The means of fat contents are included in Table 4.4. Fat content in the breading portion of baked chicken nuggets ranged from 0.35 to 0.37g/g while the fat content of the core portions ranged from 0.29 to 0.31g/g.

Table 4.4. Mean values for breading and core fat contents at different baking temperatures and times.

Baking Temperature (°C)	Baking time (min)	Breading Fat g/g db	Core Fat g/g db
Control	Control	0.36	0.30
200	10	0.37	0.29
	15	0.35	0.30
	20	0.37	0.30
	25	0.36	0.31
220	10	0.35	0.31
	15	0.37	0.32
	20	0.36	0.31
	25	0.37	0.31
240	10	0.36	0.30
	15	0.37	0.32
	20	0.37	0.30
	25	0.36	0.31

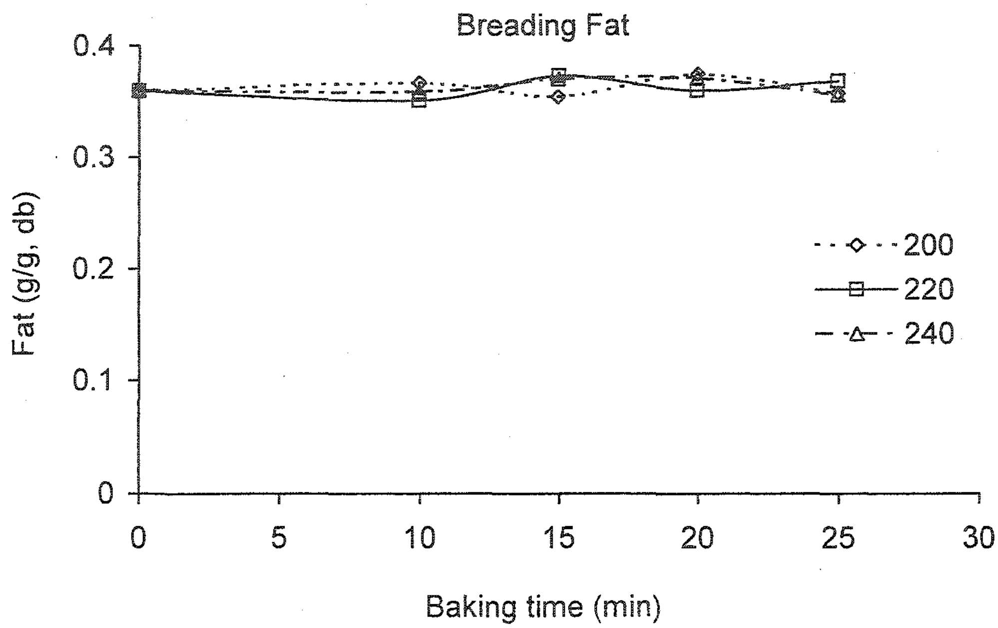

Figure 4.7. Average fat content of the breading portion of chicken nuggets during oven baking at 200, 220 and 240°C

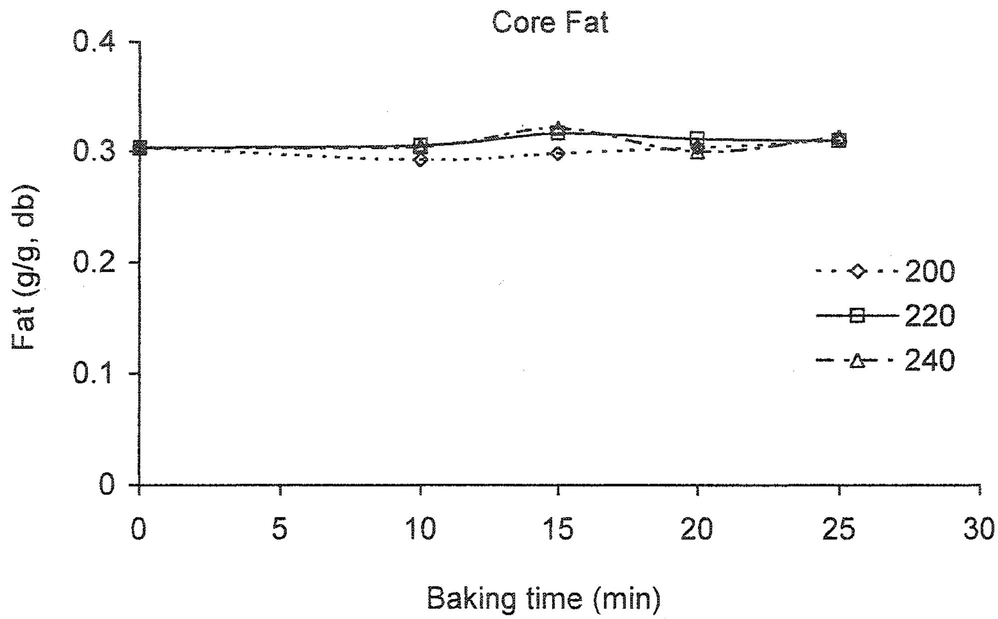

Figure 4.8. Average fat content of the core portion of chicken nuggets during oven baking at 200, 220 and 240°C.

4.3. TEXTURE AND COLOR RESULTS

4.3.1. Texture and color properties of deep fat fried chicken nuggets

Crispness and color properties are very important characteristics of breaded food products, particularly chicken nuggets. These parameters were evaluated in this study. Crispness of the product was represented by the maximum load values encountered during an INSTRON puncture test.

The effect of temperature on the maximum load values was significant ($p<0.05$). Higher frying temperature resulted in higher maximum load values. The effect of the treatment combinations of temperature and time, as well, had significant effect on maximum load. The obtained results for maximum loads are presented in Figure 4.9 and the mean separation is given in Table 4.5.

Table 4.5. Mean values for Maximum load at different frying temperatures and times.

Frying Temperature (°C)	Frying time (min)	Maximum Puncture Load (N)
Control	Control	0.60 A*
150	1	3.29 B
	2	3.53 BC
	3	3.91 CDE
	4	3.96 DE
170	1	3.76 CD
	2	3.58 BCD
	3	4.53 FG
	4	4.60 G
190	1	3.68 BCD
	2	4.19 EF
	3	4.79 G
	4	6.10 H

*Means with the same letter are not significantly different (Using Duncan's Multiple range test at alpha level = 0.05)

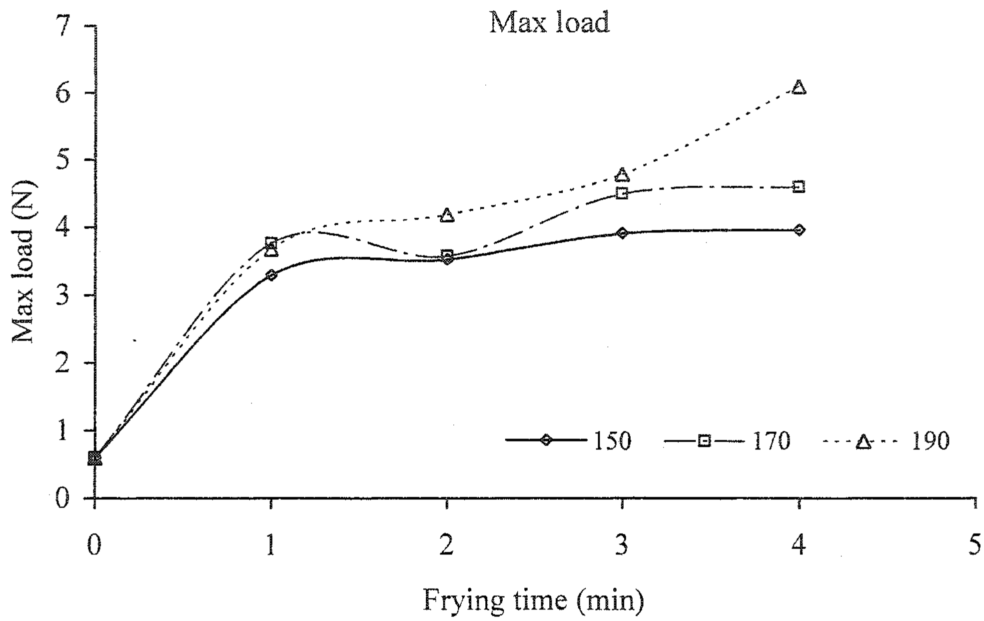

Figure 4.9. Average maximum puncture load values for chicken nuggets fried at various temperatures.

Comparing the means of maximum loads for all the combinations of time and temperatures used in this experiment, it was observed that all fried samples had significantly higher maximum load values as compare to the control. For 150°C, it was noticed that the maximum load obtained after 4 min of frying was significantly higher than those obtained after 1 and 2 min of frying. For 170°C, the maximum load values did not change significantly during the first two min of frying, then maximum load significantly increased at 3 min but did not change for 4 min of frying. For 190°C, the maximum load value increased significantly with every minute of frying, until it reaches a high of 6.1 N.

The most prominent change in terms maximum load values was observed during the initial phase of frying. The control un-fried nuggets were tested for maximum load and the mean value obtained was very low at 0.6 N, which reflected the mushy and soft texture of thawed uncooked chicken nuggets used in this study. However, upon frying, the texture toughened as reflected by the maximum load values obtained after 1 min of frying regardless of the frying temperature.

The changes in the textural properties of the fried chicken nuggets reflected by the increase in maximum puncture load were due to the physiochemical changes taking place particularly in the batter/breading portions. Moisture loss, protein denaturation and starch gelatininzation were reported as the major factors influencing textural changes in batter and breading systems (Sudderman, 1983; Loewe, 1993). Thus, the rapid increase in the maximum load values during the first min of frying could be associated with fast moisture loss in the breading portion of the chicken nuggets during early stages of frying. Indira et al. (1999) reported increasing maximum force values on samosa casing fried at different temperatures, but the pattern was different from what was observed in this study. The maximum load on samosa casing followed a linear increasing rate up till 6-7 min of frying, and then it increased more rapidly at later stages of frying. The maximum load values reported by Indira et al. (1999) varied with frying temperature. Higher frying temperatures resulted in higher maximum load values, which is similar to what was observed in this study.

Ateba and Mittal (1994) performed similar puncture tests on deep fat fried meatballs to evaluate their firmness. They obtained maximum force values comparable with the observations in this study. Those values ranged from about 0.2 N at time 0 to around 3 N after 10 min of frying. However, Ateba and Mittal (1994) found that the firmness in texture increased linearly with frying time unlike the observations made in this study. That difference in the rates of textural changes between the meat balls and chicken nuggets might be due to the difference in size and composition of the two products. The meat balls were made of homogeneous material throughout and weighed about 60 g each (Ateba and Mittal, 1994),while the chicken nuggets were composed of two different portions, the core and the breading, and they weighed 21 g each. Thus, the chicken nuggets were faster at in forming a crispy texture than the meatballs.

The L, a and b color system was used to evaluate color changes in chicken nuggets during deep fat frying. This system is one of the uniform color spaces recommended by the CIE (Commission Internationale de l'Eclairage) in 1976 as a way of closely representing perceived color. L is the lightness factor that gives values ranging form 0 (for black) to 100 (for white) while a and b are chromaticity coordinates. The a value indicates the degree of greenness-redness (ranging from –60 to 0 for green and from 0 to +60 for red) and the b value indicates the blueness-yellowness (ranging from –60 to 0 for blue and from 0 to +60 for yellow). The L, a and b color values of the fried chicken nuggets were measured and the results are presented in Figures 4.10, 4.11 and 4.12 respectively.

In general, the lightness (L) and yellowness (b) of the chicken nuggets decreased with frying time as observed in Figures 4.10 and 4.12 respectively, whereas the redness (a) followed an increasing trend (Figure 4.11). The mean separation for all color parameters is presented in Table 4.6.

Table 4.6. Mean values for L a and b color parameters for different frying temperatures and times.

Frying Temperature (°C)	Frying time (min)	L^* color values (lightness)	a^* color values (redness)	b^* color values (yellowness)
Control	Control	57.88 A*	11.96 BC*	48.84 B*
150	1	58.42 A	10.86 A	50.35 A
	2	56.08 B	12.17 BCD	45.83 CD
	3	53.83 C	12.28 CD	45.55 CD
	4	53.01 C	12.76 D	45.12 D
170	1	56.19 B	11.53 AB	46.44 C
	2	52.96 C	13.58 E	45.55 CD
	3	48.94 E	16.27 G	42.24 E
	4	46.16 F	17.97 I	39.44 F
190	1	50.22 D	14.73 F	42.24 E
	2	45.48 F	16.93 GH	38.47 G
	3	42.49 G	17.23 H	34.51 H
	4	39.27 H	16.83 GH	31.19 I

*Means with the same letter are not significantly different (Using Duncan's Multiple range test at alpha level = 0.05)

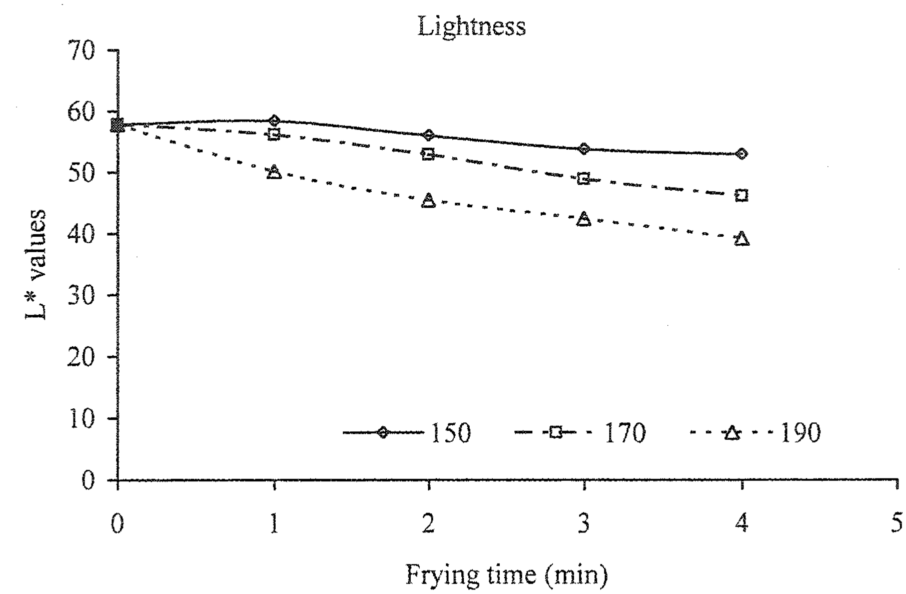

Figure 4.10. Average lightness values (L^*) obtained for chicken nuggets fried at different temperatures.

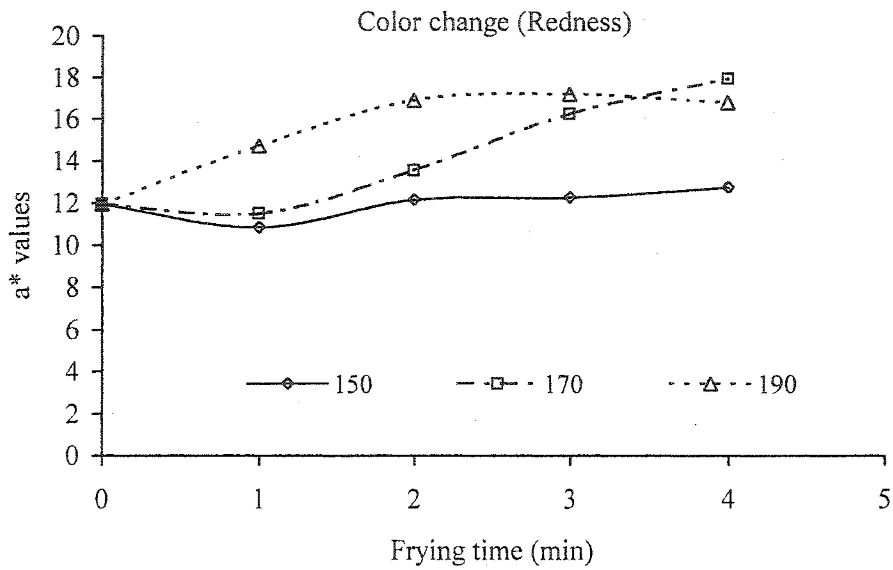

Figure 4.11. Average Redness values (a^*) obtained for chicken nuggets fried at different temperatures.

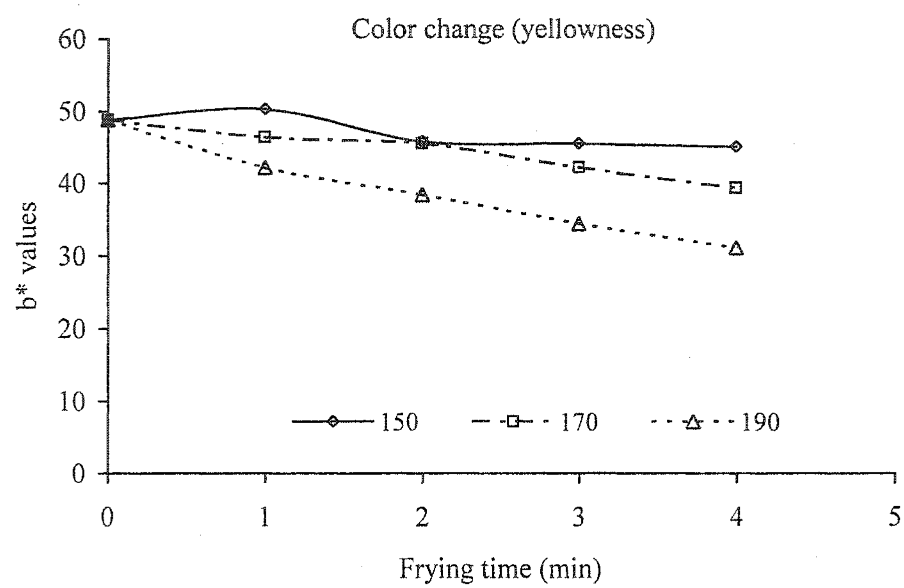

Figure 4.12. Average Yellowness values (b^*) obtained for chicken nuggets fried at different temperatures.

The effect of frying temperature proved to be significant on all the of the 3 color parameters ($p<0.05$) (Appendix I-F to I-H). Lightness and yellowness values decreased significantly with increasing frying temperature, while redness values followed an opposite trend and increased significantly with higher frying temperatures.

Comparing the lightness (L) of chicken nuggets fried at different temperatures for various lengths of time, the following were observed: For 150°C, the lightness values decreased significantly with frying time, hence the chicken nuggets became "darker" in color with frying time. For 170°C, the lightness decreased significantly with every min of frying. Frying at 190°C gave significantly lower lightness values with every min of frying. In general, the lightness of chicken nuggets decreased continuously with frying time, and was affected negatively by frying temperature. Frying for the same time at a higher temperature resulted in darker color in chicken nuggets. As in most fried products, darker colors are not desirable in fried chicken nuggets. Krokida et al. (2001) reported different results on fried potatoes. They found that the lightness of potato strips increased during early stages of frying and then remained almost constant afterwards, giving equilibrium L values ranging from 74 to 78. The difference between the results reported in this study and Krokida et al. (2001) might be due to the intrinsically different compositions between raw potatoes and the chicken nuggets. However, Krokida et al. (1999) found that increasing frying temperature results in lower lightness values, which agrees with what was observed in this study. Ateba and Mittal (1994) reported an exponential-decay decreasing pattern in the lightness of meatballs upon deep fat frying (L values dropped from 50 at time 0 to less than 25 after 10 min of frying). The raw meatballs were generally darker in color than the non-fried chicken nuggets used in this study. As reported by Ateba and Mittal (1994), the trend followed by the L values between 5 and 11 min of frying was almost linear, which resembles the trend of L values observed in this study. This could be attributed to the fact that the chicken nuggets used in this study were already par-fried and not totally raw. In other words, the lightness of the chicken nuggets had already been developed into darker values as part of the preparation process by the manufacturer.

Redness is not a desirable color in fried food products in general (Krokida et al., 2001). Mean separation analysis for the redness (a values), gave the following results: For 150°C, the redness of chicken nuggets decreased significantly between 1 and 2 min of frying then it increased significantly after 3 min of frying. For 170°C, the redness followed an increasing trend with significantly higher a values for every additional min of frying. For 190°C, the redness increased significantly between 1 and 2 min of frying then it experienced no significant change upon frying for 3 or 4 min. Frying temperature had a significant effect on redness values. Redness of chicken nuggets increased significantly with every higher level of oil temperatures. Same observation was made by Krokida et al (2001) on fried potato strips where the redness increased linearly with frying time and similar effect of frying temperature was reported.

Yellowness is a desirable color in fried products particularly in chicken nuggets whose name stresses the importance of the golden color. The yellowness or b color values followed a similar pattern as the L parameter which represents lightness in color. At 150°C frying temperature, the yellowness dropped significantly between 1 and 2 min of frying then it did not change upon further frying. For 170°C, the yellowness of the chicken nuggets followed a decreasing trend with significantly lower values after 3 and 4 min of frying. For 190°C, the yellowness of the chicken nuggets followed a steeper and more pronounced decreasing trend. The b values, at 190°C, were significantly lower with every frying min. Exponential decay in yellowness values was reported on deep fat fried meatballs (Ateba and Mittal, 1994). However, the meatballs were raw upon the onset of frying in the case of Ateba and Mittal (1994), while the chicken nuggets were already par-fried by the manufacturer, hence, certainly the color of the chicken nuggets had already been partially developed before deep fat frying in this study.

Frying temperature had a significant effect on the yellowness of chicken nuggets. The means of b values obtained were significantly lower with every increase in frying temperature.

Most of the color changes taking place in the chicken nuggets upon frying could be attributed to the browning occurring due to the presence of reducing sugars in the breading portions of the chicken nuggets. These sugars combine with amines from the protein ingredients of the breading/batter system to form a combination that undergoes non-enzymatic browning known as the Maillard reaction.

4.3.2. Texture and color properties of oven baked chicken nuggets

The means of the maximum load values representing crispness of baked chicken nuggets are presented in Figure 4.13 and Table 4.7. It was observed that the maximum recorded load increased generally with baking time. This increasing trend more consistent throughout baking at the highest baking temperature of 240°C than at 200 and 220°C. This was verified statistically. The effect of baking temperature on the maximum load was significant. Maximum load mean at 240°C was significantly higher than the maximum load means obtained at 200 and 220°C (Appendix II-E). The ANOVA procedure showed significant effect ($p<0.05$) of the various treatments of baking temperatures and times used in this experiment on the maximum load values obtained from the INSTRON puncture tests (Table 4.7). All the baking time-temperature combinations resulted in higher maximum load values than the control, which was at a low of 0.59 N.

Table 4.7. Mean values for Maximum load at different frying temperatures and times.

Baking Temperature (°C)	Baking time (min)	Maximum Puncture Load (N)
Control	Control	0. 59 A*
200	10	3.66 B
	15	3.98 B
	20	4.83 C
	25	5.59 D
220	10	3.52 B
	15	3.61 B
	20	4.93 C
	25	5.73 D
240	10	3.96 B
	15	5.98 D
	20	6.39 E
	25	7.36 F

*Means with the same letter are not significantly different (Using Duncan's Multiple range test at alpha level = 0.05)

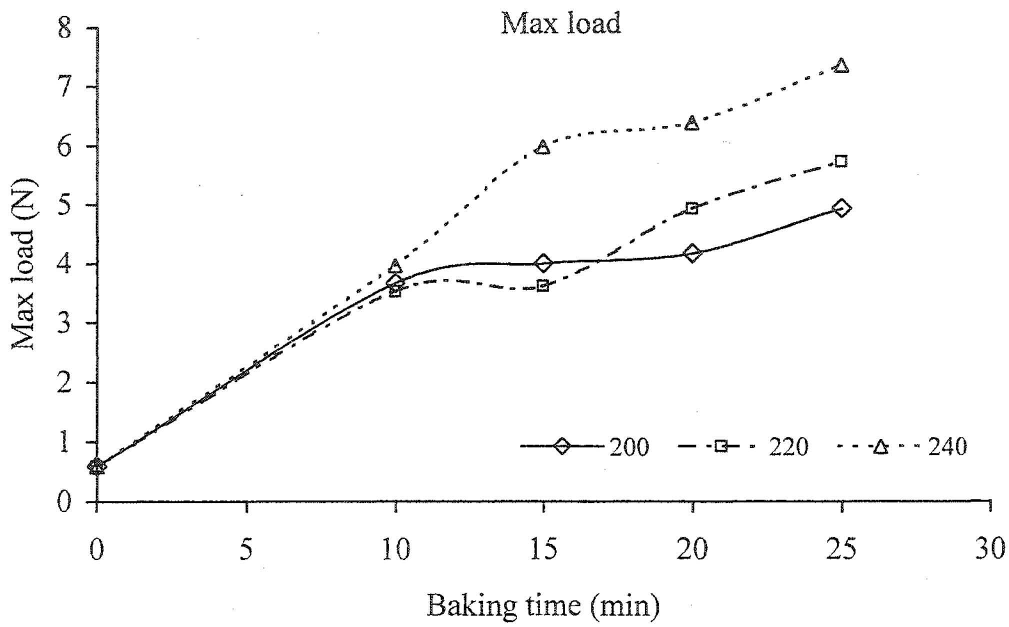

Figure 4.13. Average maximum puncture load values for chicken nuggets baked at various temperatures.

For 200°C baking temperature, the maximum load increased significantly to a high of 5.59 N after 25 min of baking. During early stages of baking at 10 and 15 min the maximum load did not change significantly. For 220°C baking temperature, exactly the same trend was observed as in 200°C. As for baking temperature of 240°C, the maximum load increased significantly at every baking time interval, and it reached a high of 7.36 N, which was significantly higher than all the recorded maximum load values. In general, it was observed that the maximum load values obtained from oven baked chicken nuggets were higher than those obtained for deep fat fried samples, which could be simply due to the longer cooking times adopted in oven baking. Moreover, in oven baking, the maximum load increases consistently with baking time, whereas the rate of increase in the case of deep fat fried samples was lower at later stages of frying. This could be attributed to the oil absorbed in fried samples and its interference with the texture of the chicken nuggets, which is a factor that does not exist in the case of oven baking.

Concerning the color changes in chicken nuggets during baking, the results are presented in Figures 4.14, 4.15 and 4.16. The ANOVA showed significant effect of the treatments of different baking time and temperature combinations on all the three-color parameters, L, a and b (Appendix II-G to II-H). Mean separation was performed and the results are included in Table 4.8.

The effect of baking temperature on the lightness and yellowness was significant ($p<0.05$). Both L (lightness) and b (yellowness) values were significantly higher at 220°C than at 200 and 240°C.

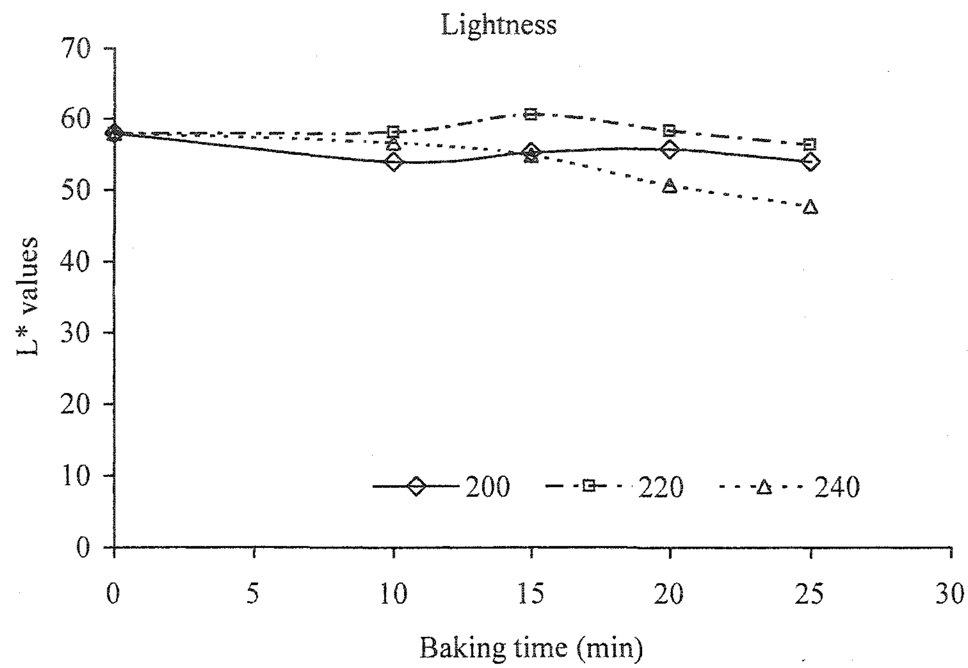

Figure 4.14. Average lightness values (L*) obtained for chicken nuggets baked at different temperatures.

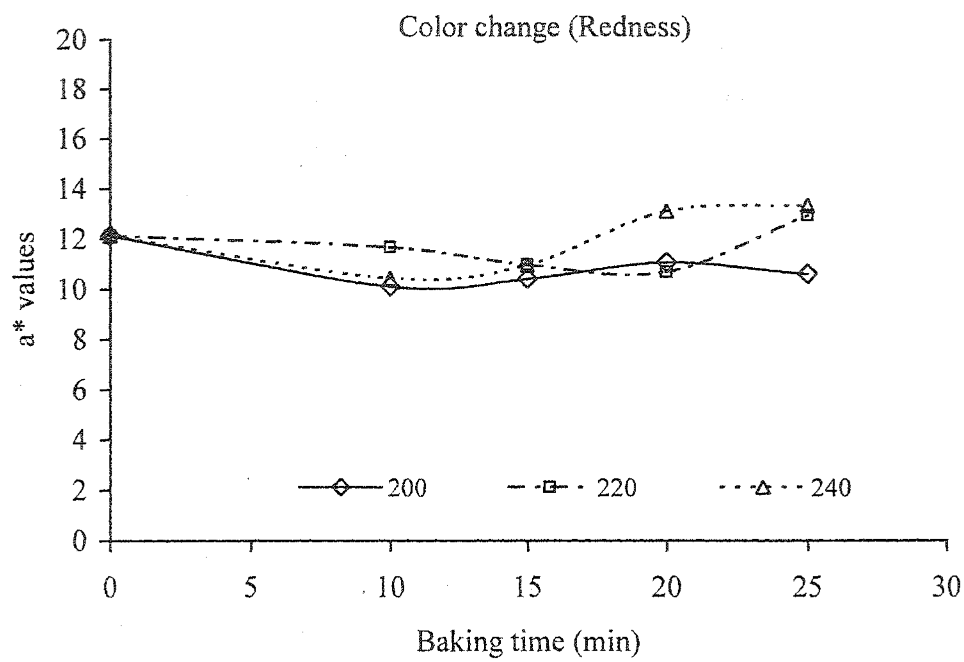

Figure 4.15. Average redness values (a^*) obtained for chicken nuggets baked at different temperatures.

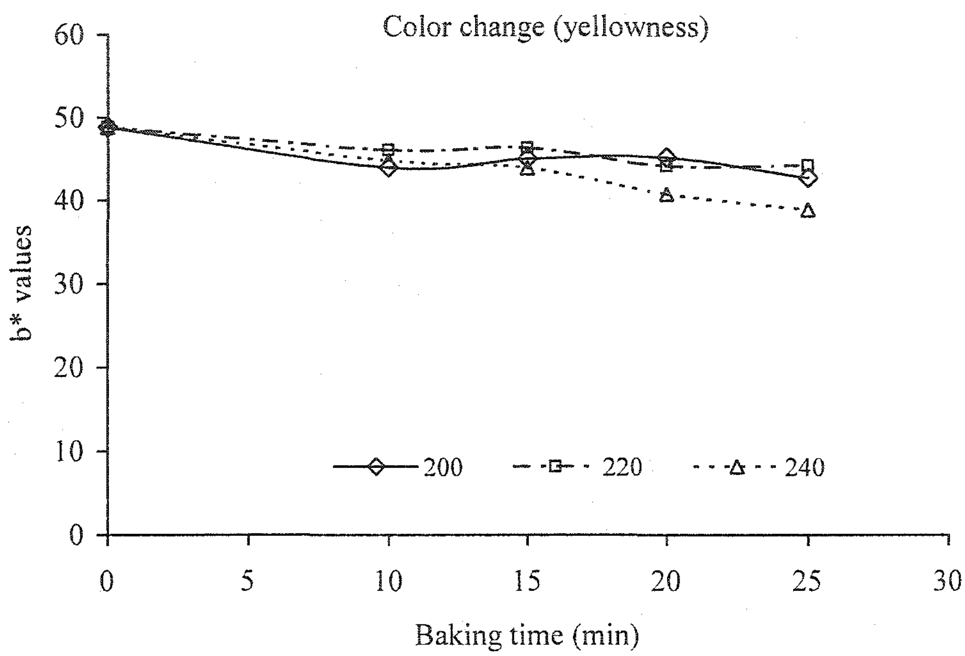

Figure 4.16. Average yellowness values (b^*) obtained for chicken nuggets baked at different temperatures.

Table 4.8. Mean values for L, a, and b color parameters of chicken nuggets baked at different temperatures.

Baking Temperature (°C)	Baking time (min)	L color values (lightness)		a color values (redness)		b color values (yellowness)	
Control	Control	57.91	BC*	12.13	D*	48.83	A*
200	10	53.98	F	10.11	A	43.99	EF
	15	55.32	EDF	10.42	AB	45.04	CDE
	20	55.81	ED	11.07	BC	45.21	CD
	25	54.11	F	10.60	AB	42.74	G
220	10	58.16	B	11.67	CD	46.07	BC
	15	60.63	A	10.97	B	46.36	B
	20	58.42	B	10.69	AB	44.17	DEF
	25	56.47	D	12.93	E	44.24	DEF
240	10	56.66	CD	10.45	AB	44.81	DEF
	15	54.93	EF	10.96	B	43.92	F
	20	50.79	G	13.10	E	40.78	H
	25	47.86	H	13.33	E	38.90	I

*Means with the same letter are not significantly different (Using Duncan's Multiple range test at alpha level = 0.05)

At 200°C baking temperature, the L values were significantly lower than the control. However, the samples did not show any prominent trend between different baking times. Similar observation was made for a and b values at 200°C. The fact that all the color parameters decreased upon baking at 150°C without showing any obvious trend with baking time could be attributed only to the loss of moisture. The cooking intensity at this temperature and within the baking times used was just enough to remove moisture without triggering any cooking-induced browning. Moisture loss alone might have caused a decrease in the color intensity for all the color parameters measured. In other words, all the color parameters faded away at this baking temperature.

For 220°C baking temperature, the lightness (L) and redness (a) values tended to fluctuate around the control without showing clear trends. However the yellowness parameter b decreased with baking time, while all the baked samples had significantly lower yellowness, which means that the nuggets generally acquired a darker color with baking.

For 240°C baking temperature, the lightness showed a clear decreasing trend as the L values were significantly lower at every baking interval. Same trend was observed with the yellowness parameter b while the redness parameter a of baked nuggets fluctuated below and above that of the control.

The most prominent factor in influencing the color parameters, particularly the lightness and yellowness, was the baking temperature. Increasing the baking temperature from 200 to 220°C resulted in significantly higher "lightness" and "yellowness". Upon further increase in baking temperature form 220 to 240°C, the lightness and yellowness were significantly lower. This could be due to the influence of two factors involved in color change in the breading portion. These factors are moisture content and non-enzymatic browning (Maillard reaction). The lower and medium baking temperature levels of 200 and 220°C used in this experiment were just enough to drive moisture loss without triggering the Maillard reaction. Moisture loss alone without browning yielded lighter colored and more yellowish chicken nuggets. Whereas, the higher baking temperature of 240°C was intense enough to initiate more browning effect, which resulted in darker chicken nuggets.

4.4. MODELING MOISTURE LOSS AND MOISTURE DIFFUSIVITY

Oven baking could be considered as a high-temperature, fast drying operation; thus, moisture loss is the major transport phenomenon that takes place. Deep fat frying, as well, causes drying of food products; moreover, the fat absorption taking place during frying was often associated with moisture dynamics in the fried food. Several authors correlated fat absorption and moisture loss; a linear relationship was reported throughout deep fat frying between oil uptake and moisture loss (Gamble et al., 1987; Krokida, 2000). During frying, moisture loss creates cavities or pores as well as passageways in the food. These cavities are known as capillary pores and through them oil penetrates fried products during frying. So, predicting water loss is critical for modeling and controlling deep fat frying and oven baking operations.

Fick's second law of diffusion (Equation 4.1) was often used as the governing equation for mass transfer during dehydration of food materials (Zogzas and Maroulis, 1996) and during deep fat frying (Moreira et al., 1991).

$$\frac{\delta(\rho_s M)}{\delta t} = \nabla(D\rho_s \nabla M) \tag{4.1}$$

Where,

M is moisture content on dry basis (kg/kg)

ρ_s is the concentration of dry solids (kg/m^3)

t is time in seconds

D is the moisture diffusivity (m^2/s)

Assume constant moisture diffusivity, no change in volume and change in dry matter due to oil uptake hence constant density of dry matter, Equation 4.1 will then be reduced to:

$$\frac{\delta M}{\delta t} = D\nabla^2 M \tag{4.2}$$

Furthermore, the chicken nugget can be considered as an infinite plate with thickness L, then one dimensional moisture movement will take place and equation 4.2 can be written as:

$$\frac{\delta M}{\delta t} = D\frac{\delta^2 M}{\delta x^2} \tag{4.3}$$

where D is the diffusivity, L is the plate thickness

The solution to Equation 4.3 is found in Crank (1975) considering the assumptions of uniform initial moisture content, negligible external resistance to moisture transfer, and the following initial and boundary conditions:

$M(x,0) = M_o$, uniform initial moisture content in breading

$M(x_o,t) = M_e$, final moisture content at the product surface

Thus the solution of Equation 4.3 subject to the stated boundary conditions was given as (Crank, 1975):

$$M_r = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-(2n+1)^2\frac{\pi^2 Dt}{L^2}\right] \tag{4.4}$$

Where $M_r = (M - M_e)/(M_o - M_e)$; M is average moisture content at time t (kg/kg d.b.), M_o is initial moisture content, and M_e is equilibrium moisture content, D is moisture diffusivity (m^2/s), t is time in seconds, and L is plate thickness (m).

The first term of the series in Equation 4.4 would provide a close approximation. All the other terms of the series are small fractions and can be neglected, thus we obtain:

$$M_r = \frac{M - M_e}{M_o - M_e} = \frac{8}{\pi^2} \exp(-\frac{\pi^2 Dt}{L^2}) \quad (4.5)$$

By simple manipulation of Equation 4.5 the moisture content at time t can be expressed as follows:

$$M = \frac{8}{\pi^2}(M_o - M_e)\exp(-\frac{\pi^2 Dt}{L^2}) + M_e \quad (4.6)$$

The mathematical model described above was found to be valid to describe moisture loss from the breading portion of chicken nuggets. The assumptions on which this model is based were all applicable for the chicken nugget breading part. First of all the breading portion could be considered as an infinite plate due to its low thickness value (2 mm) compared to surface area (45 mm x 50 mm). Second, there was little or no shrinkage observed in the chicken nuggets during cooking, whether under deep fat frying or oven baking. Third, the initial moisture content could be considered uniform in the breading portion. However, if the breading was to be considered as an infinite plate, then moisture loss would be taking place form one surface of that plate, which is the outer surface of the breading (Figure 4.17). Thus the thickness L of the breading layer should be substituted in Equations 4.3 - 4.6 by 2L. Thus, Equation 4.6 can be used to describe moisture content at time t in the breading portions of the chicken nuggets.

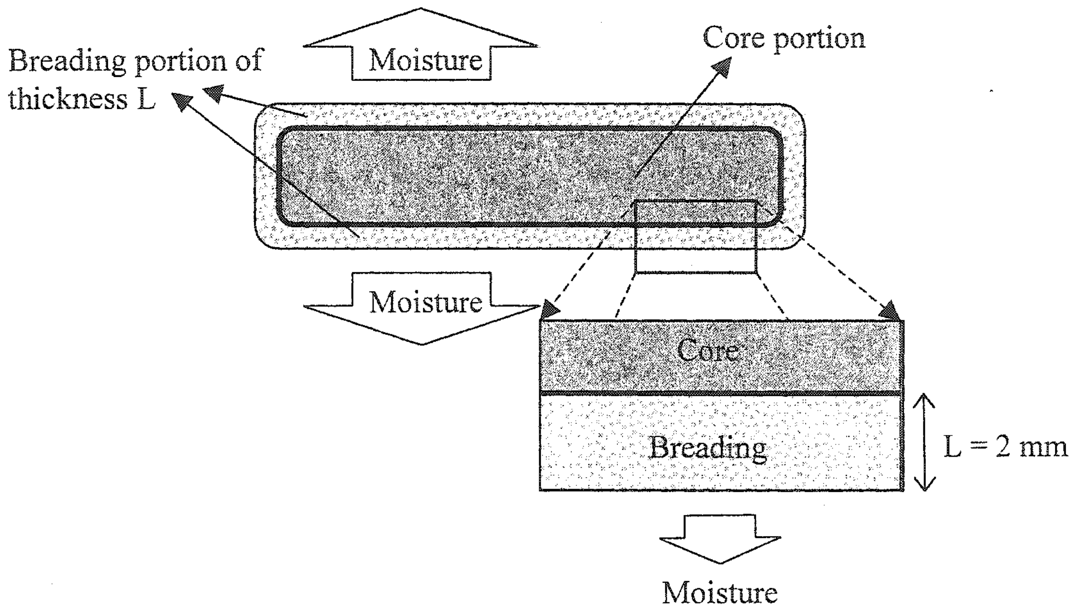

Figure 4.17. Cross sectional view of the chicken nuggets used in this experiment

Based on Equation 4.6, a non-linear regression procedure was performed by fitting the following equation to the experimental data of breading moisture of fried and baked chicken nuggets:

$$M = A_1 \exp(A_2 t) + A_3 \qquad (4.7)$$

Table 4.9. Parameters of equation 4.7 obtained upon fitting the exponential model to the experimental breading moisture content of the chicken nuggets baked and fried at different temperatures.

Cooking method and temperature	Breading moisture Model parameters A_1	A_2	A_3	$(R^2)^*$	RMS**
Deep fat frying					
150°C	0.63	-0.0129	0.28	0.9859	0.18
170°C	0.60	-0.01807	0.30	0.9984	0.02
190°C	0.66	-0.0156	0.24	0.9862	0.20
Oven baking					
200°C	0.78	-0.001169	0.12	0.9961	0.052
220°C	0.78	-0.001413	0.12	0.9985	0.024
240°C	0.76	-0.001950	0.14	0.9996	0.008

*R^2 Coefficient of determination; **RMS: residual mean square

Figure 4.18 shows the experimental and the predicted results of breading moisture content as a function of frying time for different frying temperatures. Figures 4.19 shows the experimental and the predicted results of breading moisture content as a function of baking time for different baking temperatures. The values A_1, A_2, and A_3 of Equation 4.7 are given in Table 4.9 along with the coefficients of determination for the various temperatures of oven baking and deep fat frying.

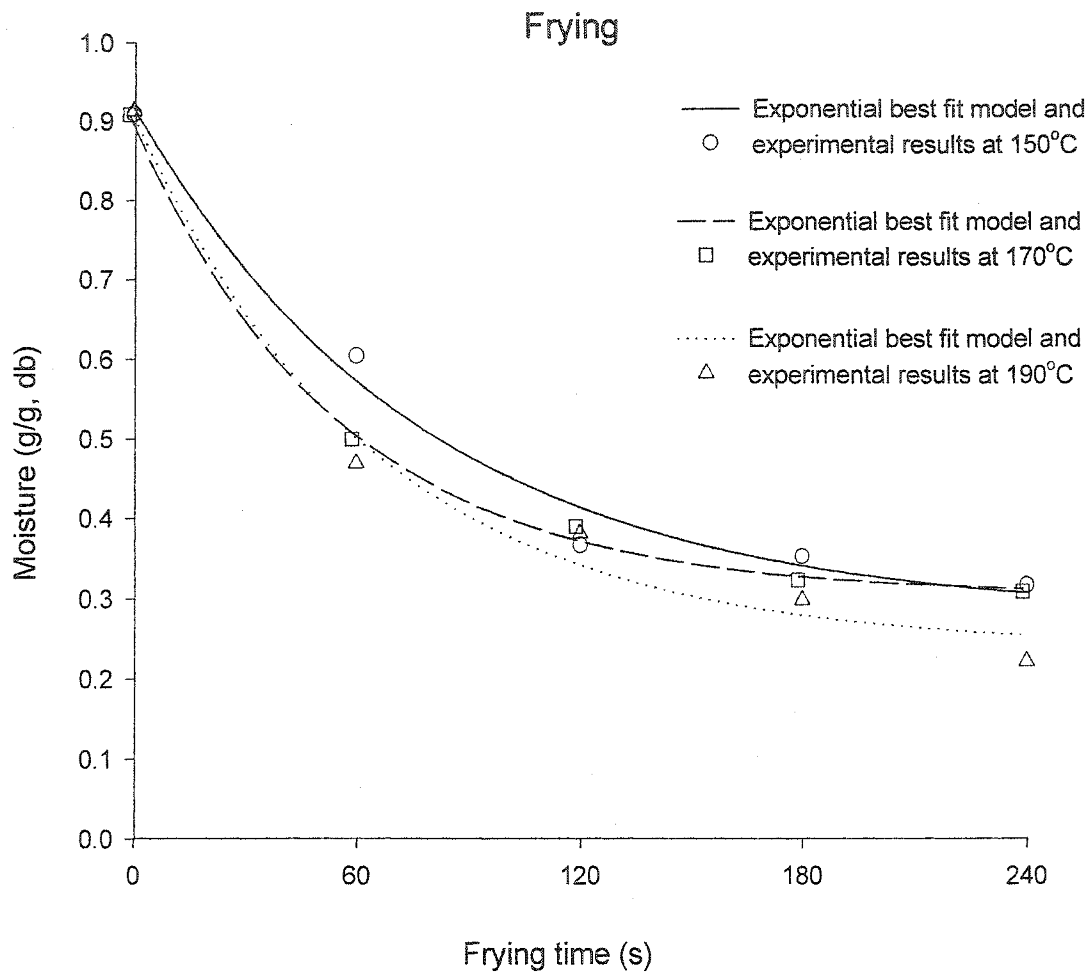

Figure 4.18. Plot of experimental breading moisture content results with best-fit exponential model (Equation 4.7) for deep fat frying at 150°C, 170°C and 190°C.

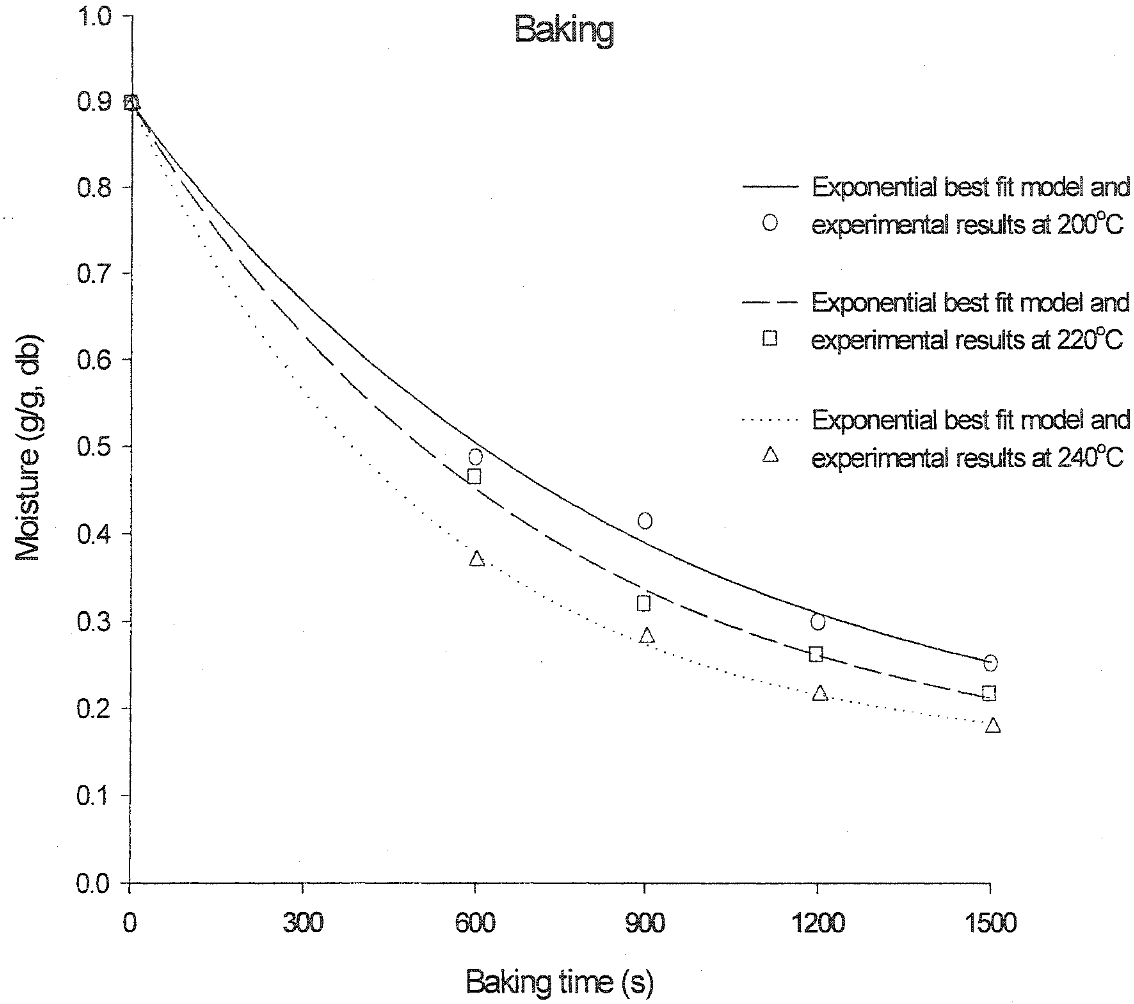

Figure 4.19. Plot of experimental breading moisture content results with best-fit exponential model (Equation 4.7) for deep fat frying at 150°C, 170°C and 190°C.

The used model gave a very good prediction of moisture loss in the breading portion of chicken nuggets during oven baking and deep fat frying. A similar modeling approach was followed by Moreira et al. (1991) to describe moisture loss in tortilla chips during deep fat frying, and good prediction of moisture loss was obtained. The parameter A_3 in Equation 4.7 is the equilibrium moisture content. The values of equilibrium moisture content obtained were close to what was reported by Krokida et al. (2001) on French fries. The authors obtained equilibrium moisture contents ranging from 0.30 to 0.80 g/g (db) depending on frying temperature. In this study and in the case of baking, equilibrium moisture content increased with higher temperature, which disagreed with what was reported by Krokida et al. (2001). Equilibrium moisture content during a typical dehydration process should actually decrease with higher temperatures. The higher equilibrium moisture contents experienced at higher baking temperatures can be explained by the onset of moisture loss from the core portions of the chicken nugget at later stages of baking. The moisture loss rate from the core portion was larger for higher baking temperatures, and since that moisture passes through the breading on its way to the surface, thus the observed equilibrium moisture content in the breading would be affected by the amount of moisture being transferred from the core. It is expected that if cooking is performed beyond the times used in this experiment, a prompt drop in moisture content will be experienced once most of the core moisture is removed. Thus the model proposed fits the moisture content data only within the cooking times used in this study.

Various equilibrium moisture content values reported in the literature were usually closer to zero (Moreira et al., 1991; Zogzas and Maroulis, 1996). The high equilibrium moisture contents obtained in this study show that the models used are useful in describing moisture loss within the cooking time durations used.

When comparing Equations 4.6 and 4.7, the parameter A_2 in Equation 4.7 is equal to the term $-\pi^2 D/L^2$, thus the diffusivity values for each frying and baking temperature could be found where: $D = - A_2 L^2/\pi^2$ where L is 2x the thickness of the breading which is 2 x 2mm = 4 mm.

Table 4.10. Moisture diffusivities in the breading portions calculated from the parameter A_2 of the exponential model (Equation 4.7).

Cooking method and temperature	Parameter A_2	Diffusivity (m^2/s) from $D = - A_2 L^2/\pi^2$
Oven baking at 200°C	-0.001169	1.897×10^{-10}
Oven baking at 220°C	-0.001413	2.293×10^{-10}
Oven baking at 240°C	-0.001950	3.164×10^{-10}
Deep fat frying at 150°C	-0.0129	20.93×10^{-10}
Deep fat frying at 170°C	-0.01807	29.32×10^{-10}
Deep fat frying at 190°C	-0.0156	25.32×10^{-10}

The obtained moisture diffusivity values ranged from 1.9×10^{-10} to 3.16×10^{-10} in oven baking depending on temperature (Table 4.10). No diffusivity values for breadings or breaded products were found in the literature. However, comparable diffusivities were obtained by Mittal and Blaisdell (1984) on meat emulsions where the estimated moisture diffusivity ranged from 1.12×10^{-10} to 5.89×10^{-10} m^2/s for temperatures ranging from 58 to 81°C. The moisture diffusivity obtained for during deep fat frying was in the range of 21 to 29 $\times 10^{-10}$ m^2/s (Table 4.10), which is within the moisture diffusivities reported by Ngadi and Correia (1995) that ranged from 13×10^{-10} to 164×10^{-10} m^2/s during deep fat frying of chicken drum muscles at temperatures ranging from 120-180°C. The moisture diffusivity values obtained for oven baked chicken nuggets increase with increasing temperature, while that was not observed for the deep fat fried chicken nuggets. The higher moisture diffusivities obtained during deep fat frying as compared to those calculated during oven baking was mainly due to the higher intensity of heat transfer encountered in deep fat frying, since heat transfer is the main driving force for moisture diffusion in both cooking methods.

The effect of temperature on moisture diffusivity has been realized by most researchers (Zogzas et al., 1996). Moisture diffusivity tends to increase with increasing temperature, and this relationship has been often described by the following Arrhenius type relationship:

$$D = D_o \exp(-\frac{E_o}{RT}) \tag{4.8}$$

Where D is moisture diffusivity in m^2/s, D_o is the Arrhenius factor m^2/s, E_o is the activation energy for moisture diffusion (kJ/mol), R is the ideal gas constant 0.0083143 kJ/(mol.°K), and T is the absolute temperature (°K).

The diffusivity of the breading portion of chicken nuggets was plotted as a function of 1/T, which is the inverse of absolute temperature (Figure 4.20), and the resulting curve was fit to an Arrhenius type model (Equation 4.9).

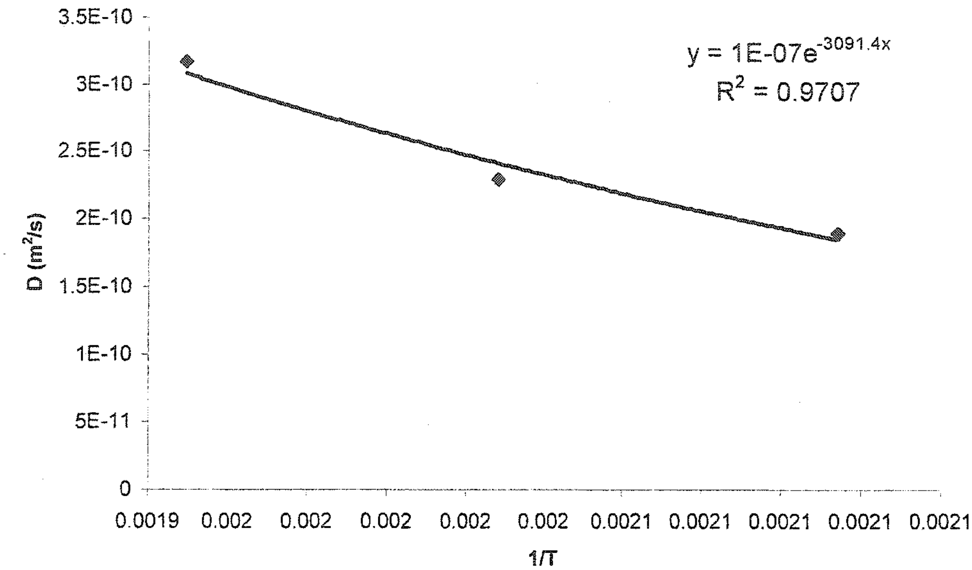

Figure 4.20. Plot of diffusivity verses the inverse of absolute temperature for the baked chicken nuggets, with the fit exponential model.

$$D = 10^{-7} \exp(-\frac{3091.4}{T}) \tag{4.9}$$

The ratio of the activation energy of moisture diffusion in the breading and the universal gas constant was 3091 K^{-1}, from which the activation energy was calculated as 25.7 kJ/mol. Activation energy is the energy needed to induce variation in diffusivity within certain conditions. The lower the activation energy, the easier the moisture transfer in a given material (Laidler, 1978). Ngadi and Correia (1995) obtained activation energy of 24 kJ/mol for moisture diffusivity in chicken drum muscle during deep fat frying at temperatures ranging from 120 to 180°C. Karathanos (1990) reported activation energies ranging from 17.9 to 26.7 kJ/mol for moisture diffusivity in granular starch at temperatures ranging from 25 to

140°C. The activation energy of moisture diffusivity in breadings of chicken nuggets obtained in this study is comparable with those obtained for other products such as starch grains, minced meat, and chicken drums. This provides a better understanding of the moisture diffusion phenomenon in breaded food products during cooking.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1. General Conclusions

Moisture content of the breading portion of the fried chicken nuggets decreased following a typical drying curve and ranged from 0.90 g/g (control, on dry basis) to 0.22 g/g (frying at 190°C for 4min), while the moisture content of the core portion of the chicken nuggets decreased almost linearly and ranged from 1.96 g/g (control) to 1.4 g/g (frying at 190°C for 4 min). This difference in the moisture loss kinetics from the two different portions of the chicken nuggets indicates the influence of the batter/breading coating in retarding moisture loss from the core. The effect of frying temperature proved to be significant ($p<0.05$) on the moisture content of both portions of the chicken nuggets. Higher frying temperatures yielded lower moisture contents. Fat content of breading portion increased linearly and ranged from 0.35 g/g (control) to 0.42 g/g (frying at 190°C for 4 min), while that of the core portion ranged from 0.30 g/g (control) to 0.38 g/g (frying at 170 or 190°C for 4 min) and it also showed linear increase with time. Frying temperature significantly affected the fat content of the core but not that of the breading. The fat content of the core, generally increased with higher frying temperature.

In the case of oven baking, the moisture content of the breading portion of the chicken nuggets ranged from 0.90 g/g (control) to 0.18 g/g (baking at 240°C for 25 min) following patterns similar to those of the moisture content of the breading portion of fried chicken nuggets. Meanwhile, the moisture content of the core portion of the baked chicken nuggets did not change except after considerable baking time (>10 min) and it ranged from 2 g/g (control) to 0.87 g/g (baking at 240°C for 25 min). Baking temperature had a highly significant effect on moisture contents of both potions of the chicken nuggets. The fat content of both portions of the baked chicken nuggets did not change throughout baking regardless of the temperature used.

The moisture loss from the breading portion turned out to be similar in both cooking methods, which was not the case for moisture loss from the core portions of the chicken nuggets. In Conclusion, baking for medium-range times tends to yield similar breading moistness to deep fat frying, while better retaining the core moisture, which might be a desirable moisture configuration in the final product.

The color of deep fat fried and oven baked chicken nuggets was also evaluated using L a b color system. In deep fat frying, the lightness (L) and yellowness (b) parameters decreased with longer frying time and higher frying temperatures while the redness (a) parameter increased with frying time and temperature. In the case of oven baking, the lightness and yellowness parameters increased then decreased with baking time. The effect of baking temperature was significant; baking at 220°C gave higher lightness and yellowness than at 200°C, while baking at 240°C gave lower values than at 220°C.

The texture of the cooked chicken nuggets was evaluated using a puncture INSTRON test. The maximum load encountered during the puncture test was recorded and considered as an indication of the crispness of the chicken nuggets. In deep fat frying the maximum load ranged from 0.6N (control) to 6.1 N (frying at 190°C for 4 min) while in the case of oven baking, the maximum load ranged from 0.59 N (control) to 7.36 N (baking at 240°C for 25 min). The effect of cooking time and temperature, whether in frying or baking, proved to be significant on the maximum load values. These values, and hence crispness of the product, increased significantly with cooking time and with higher cooking temperatures.

Upon comparing the color and texture of deep fat fried chicken nuggets and oven baked ones, it was found that oven baking retained a lighter "golden" color than did deep fat frying. Concerning the crispness of the chicken nuggets, both cooking methods gave similar results for most of the cooking times.

The moisture loss observed in the breading portions of the chicken nuggets was modeled based on Ficks second law of diffusion. The breading portion was assumed to be an infinite slab with thickness L, and constant moisture diffusivity. Hence the first term of Crank's (1975) solution of Fick's second law was used to model moisture diffusion in the breading portion of the chicken nuggets. Based on the experimental data obtained from this study, a best-fit exponential model was plotted for every frying and baking temperature used and R^2 values obtained were all higher than 0.98. The obtained parameters of the exponential models were used to calculate the moisture diffusivities. In the case of deep fat frying the moisture diffusivities were 2.1, 2.9 and 2.5 $\times 10^{-9}$ for frying temperatures of 150, 170 and 190°C respectively. While the moisture diffusivities obtained in the case of oven baking were 1.9, 2.3 and 3.16 $\times 10^{-10}$ for baking temperatures of 200, 220 and 240°C respectively. The relationship between absolute temperature and moisture diffusivities obtained from the baking data was modeled using an Arrhenius type equation. The activation energy was determined to be 25.7 kJ/mol.

5.2. RECOMMENDATIONS

Based on the findings of this study, the following recommendations for further research work are suggested:

1. To determine the influence of various breading types and thickness on oil uptake and moisture loss in cooked chicken nuggets.
2. To study the influence of various batter compositions and viscosities on the oil uptake and moisture loss dynamics of chicken nuggets.
3. To employ more advanced testing methods for determining the moisture and fat contents in various portions of chicken nuggets. An example would be using Differential Scanning Calorimetry, which could be a fast and reliable tool in determining fat and moisture contents at very discrete points in the food sample, since it can be run on very small samples in the order of milligrams.
4. To model the relationships between textural and color characteristics of cooked chicken nuggets with the final composition (moisture and fat) on one hand, and with the cooking process parameters on the other.
5. To model the moisture loss and oil uptake dynamics in the breaded chicken nuggets as a whole.

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Appendix I

ANOVA tables and Duncan's Multiple Range mean separation obtained for deep fat frying data

I-A. ANOVA tables and mean separation for the moisture content of the breading portion of the chicken nuggets.

Dependent Variable: breading moisture
ANOVA table for the effect of the frying treatments on breading moisture

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	2.2323	0.1860	376.14	<.0001
Error	65	0.0321	0.00049		
Corrected Total	77	2.2644			

R-Square = 0.985804, CV = 5.33

ANOVA table for the effect of time, temperature and their interaction on breading moisture

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	0.02815172	0.01407586	31.73	<.0001
Time	3	0.29736275	0.09912092	223.43	<.0001
Temp*Time	6	0.02424650	0.00404108	9.11	<.0001

R-Square = 0.973065, CV = 5.59

Duncan Grouping	Mean	Temp (°C)
A	0.408917	150
B	0.379833	170
C	0.340667	190

Duncan Grouping	Mean	Time (min)
A	0.522333	1
B	0.378000	2
C	0.324000	3
D	0.281556	4

I-B. ANOVA tables and mean separation for the moisture content of the core portion of the chicken nuggets.

Dependent Variable: Core moisture
ANOVA table for the effect of the frying treatments on core moisture

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	2.0525	0.1710	46.12	<.0001
Error	65	0.2410	0.0037		
Corrected Total	77	2.2935			

R-Square = 0.8949, CV = 3.57

ANOVA table for the effect of time, temperature and their interaction on core moisture

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	0.14384439	0.07192219	13.92	0.0001
Time	3	0.64895986	0.21631995	41.88	<.0001
Temp*Time	6	0.04831672	0.00805279	1.56	0.2061

R-Square = 0.881, CV = 4.26

Duncan Grouping	Mean	Temp (°C)
A	1.76392	150
B	1.69100	170
C	1.60917	190

Duncan Grouping	Mean	Time (min)
A	1.89922	1
B	1.70333	2
C	1.60322	3
C	1.54633	4

I-C. ANOVA tables and mean separation for the fat content of the breading portion of the chicken nuggets

Dependent Variable: Breading fat
ANOVA table for the effect of the frying treatments on breading fat

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	0.0253	0.002114	17.80	<.0001
Error	65	0.00772	0.0001187		
Corrected Total	77	0.0331			

R-Square = 0.767, CV = 2.86

ANOVA table for the effect of time, temperature and their interaction on breading fat

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	0.00044517	0.00022258	2.43	0.1110
Time	3	0.00716519	0.00238840	26.11	<.0001
Temp*Time	6	0.00209306	0.00034884	3.81	0.0093

R-Square = 0.852, CV = 2.49

Duncan Grouping	Mean	Temp (°C)
A	0.387917	190
AB	0.383000	150
B	0.379333	170

Duncan Grouping	Mean	Time (min)
A	0.401889	4
B	0.387111	3
B	0.382222	2
C	0.362444	1

I-D. ANOVA tables and mean separation for the fat content of the core portion of the chicken nuggets

Dependent Variable: Core fat

ANOVA table for the effect of the frying treatments on core fat

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	0.0372	0.0031	28.40	<.0001
Error	65	0.0071	0.000109		
Corrected Total	77	0.04429			

R-Square = 0.8398, CV = 3.02

ANOVA table for the effect of time, temperature and their interaction on core fat

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	0.00298006	0.00149003	15.54	<.0001
Time	3	0.00893208	0.00297736	31.05	<.0001
Temp*Time	6	0.00168483	0.00028081	2.93	0.0296

R-Square = 0.875, CV = 2.80

Duncan Grouping	Mean	Temp (°C)
A	0.359500	170
A	0.351583	190
B	0.337500	150

Duncan Grouping	Mean	Time (min)
A	0.367556	4
B	0.357222	3
B	0.348444	2
C	0.324889	1

I-E. ANOVA tables and mean separation for the maximum load values

Dependent Variable: Maximum Load
ANOVA table for the effect of the frying treatments on Maximum load

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	145.3828846	12.1152404	82.08	<.0001
Error	91	13.4325000	0.1476099		
Corrected Total	103	158.8153846			

R-Square = 0.915, CV = 9.89

ANOVA table for the effect of time, temperature and their interaction on max load

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	8.29572917	4.14786458	21.78	<.0001
Time	3	13.09375000	4.36458333	22.92	<.0001
Temp*Time	6	4.55093750	0.75848958	3.98	0.0042

R-Square = 0.807, CV = 10.49

Duncan Grouping	Mean	Temp (°C)
A	4.6875	190
B	4.1156	170
C	3.6719	150

Duncan Grouping	Mean	Time (min)
A	4.8875	4
B	4.4083	3
C	3.7625	2
C	3.5750	1

I-F. ANOVA tables and mean separation for the lightness values

Dependent Variable: Lightness (L values)
ANOVA table for the effect of the frying treatments on Lightness (L values)

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	3516.109021	293.009085	215.37	<.0001
Error	91	123.803575	1.360479		
Corrected Total	103	3639.912596			

R-Square = 0.966, CV = 2.29

ANOVA table for the effect of time, temperature and their interaction on lightness

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	979.1365292	489.5682646	293.80	<.0001
Time	3	525.2628500	175.0876167	105.07	<.0001
Temp*Time	6	39.0775875	6.5129312	3.91	0.0047

R-Square = 0.966, CV = 2.57

Duncan Grouping	Mean	Temp (°C)
A	55.3394	150
B	51.0631	170
C	44.3650	190

Duncan Grouping	Mean	Time (min)
A	54.9442	1
B	51.5092	2
C	48.4183	3
D	46.1517	4

I-G. ANOVA tables and mean separation for the redness load values

Dependent Variable: Redness (a value)
ANOVA table for the effect of the frying treatments on redness (a values)

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	607.5163712	50.6263643	104.98	<.0001
Error	91	43.8825750	0.4822261		
Corrected Total	103	651.3989462			

R-Square = 0.933, CV = 4.88

ANOVA table for the effect of time, temperature and their interaction on redness

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	159.7956500	79.8978250	145.04	<.0001
Time	3	69.2780167	23.0926722	41.92	<.0001
Temp*Time	6	52.3432333	8.7238722	15.84	<.0001

R-Square = 0.939, CV = 5.14

Duncan Grouping	Mean	Temp (°C)
A	16.4313	190
B	14.8400	170
C	12.0188	150

Duncan Grouping	Mean	Time (min)
A	15.8583	4
A	15.2625	3
B	13.7917	2
C	12.8075	1

I-H. ANOVA tables and mean separation for the yellowness values

Dependent Variable: Yellowness (b value)
ANOVA table for the effect of the frying treatments on yellowness (b values)

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	2965.414937	247.117911	307.48	<.0001
Error	91	73.135325	0.803685		
Corrected Total	103	3038.550262			

R-Square = 0.976, CV = 2.097

ANOVA table for the effect of time, temperature and their interaction on yellowness

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	850.8272375	425.4136187	434.67	<.0001
Time	3	401.7311083	133.9103694	136.82	<.0001
Temp*Time	6	69.3350292	11.5558382	11.81	<.0001

R-Square = 0.976, CV = 2.34

Duncan Grouping	Mean	Temp (°C)
A	46.7150	150
B	43.4194	170
C	36.6044	190

Duncan Grouping	Mean	Time (min)
A	46.3442	1
B	43.2883	2
C	40.7692	3
D	38.5833	4

Appendix II

ANOVA tables and Duncan's Multiple Range mean separation obtained for baking data

II-A. ANOVA tables and mean separation for the moisture content of the breading portion of the baked chicken nuggets

Dependent Variable: Breading moisture
ANOVA table for the effect of the baking treatments on breading moisture

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	2.5662	0.2138	278.36	<.0001
Error	65	0.04994	0.000768		
Corrected Total	77	2.6162			

R-Square = 0.981, CV = 7.69

ANOVA table for the effect of time, temperature and their interaction on breading moisture

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	0.04940000	0.02470000	33.72	<.0001
Time	3	0.27058889	0.09019630	123.12	<.0001
Temp*Time	6	0.01977778	0.00329630	4.50	0.0041

R-Square = 0.956, CV = 8.59

Duncan Grouping	Mean	Temp (°C)
A	0.36333	200
B	0.30833	220
C	0.27333	240

Duncan Grouping	Mean	Time (min)
A	0.44333	10
B	0.34111	15
C	0.26000	20
D	0.21556	25

II-B. ANOVA tables and mean separation for the moisture content of the core portion of the baked chicken nuggets

Dependent Variable: Core moisture
ANOVA table for the effect of the baking treatments on core moisture

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	8.7511	0.7292	199.22	<.0001
Error	65	0.2379	0.00366		
Corrected Total	77	8.9890			

R-Square = 0.974, CV = 3.41

ANOVA table for the effect of time, temperature and their interaction on core moisture

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	0.77513356	0.38756678	75.41	<.0001
Time	3	2.83964856	0.94654952	184.17	<.0001
Temp*Time	6	0.61141511	0.10190252	19.83	<.0001

R-Square = 0.974, CV = 4.08

Duncan Grouping	Mean	Temp (°C)
A	1.95017	200
B	1.72833	220
C	1.59433	240

Duncan Grouping	Mean	Time (min)
A	2.01944	10
B	1.90356	15
C	1.82067	20
D	1.28678	25

II-C. ANOVA tables and mean separation for the fat content of the breading portion of the baked chicken nuggets

ANOVA table for the effect of time, temperature and their interaction on breading fat

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	0.00000539	0.00000269	0.02	0.9804
Time	3	0.00055431	0.00018477	1.36	0.2810
Temp*Time	6	0.00159261	0.00026544	1.95	0.1166

R-Square = 0.477, CV = 3.21

Duncan Grouping	Mean	Temp (°C)
A	0.364000	240
A	0.363333	200
A	0.363083	220

Duncan Grouping	Mean	Time (min)
A	0.368556	20
A	0.365889	15
A	0.360667	25
A	0.358778	10

II-D. ANOVA tables and mean separation for the fat content of the core portion of the baked chicken nuggets

ANOVA table for the effect of time, temperature and their interaction on core fat

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	0.00071517	0.00035758	2.48	0.1070
Time	3	0.00086097	0.00028699	1.99	0.1450
Temp*Time	6	0.00072861	0.00012144	0.84	0.5514

R-Square = 0.449, CV = 3.90

Duncan Grouping	Mean	Temp (°C)
A	0.311583	220
A	0.310167	240
A	0.301500	200

Duncan Grouping	Mean	Time
A	0.312667	15
A	0.312000	25
A	0.305556	20
A	0.300778	10

II-E. ANOVA tables and mean separation for maximum load values of the baked chicken nuggets

Dependent Variable: Maximum load
ANOVA table for the effect of the baking treatments on maximum load

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	280.1086538	23.3423878	72.11	<.0001
Error	91	29.4562500	0.3236951		
Corrected Total	103	309.5649038			

R-Square = 0.905, CV = 12.30

ANOVA table for the effect of time, temperature and their interaction on max load

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	22.22010417	11.11005208	29.46	<.0001
Time	3	42.17604167	14.05868056	37.27	<.0001
Temp*Time	6	5.05239583	0.84206597	2.23	0.0644

R-Square = 0.852, CV = 12.38

Duncan Grouping	Mean	Temp (°C)
A	5.9219	240
B	4.5125	200
B	4:4469	220

Duncan Grouping	Mean	Time (min)
A	6.2250	4
B	5.3792	3
C	4.5208	2
D	3.7167	1

II-F. ANOVA tables and mean separation for lightness values of the baked chicken nuggets

Dependent Variable: Lightness (L values)
ANOVA table for the effect of baking treatments on Lightness (L values)

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	1082.763663	90.230305	51.86	<.0001
Error	91	158.328162	1.739870		
Corrected Total	103	1241.091826			

R-Square = 0.872, CV = 2.38

ANOVA table for the effect of time, temperature and their interaction on lightness

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	280.0469625	140.0234813	65.68	<.0001
Time	3	119.5389833	39.8463278	18.69	<.0001
Temp*Time	6	115.8467542	19.3077924	9.06	<.0001

R-Square = 0.880, CV = 2.64

Duncan Grouping	Mean	Temp (°C)
A	58.4231	220
B	54.8044	200
C	52.5600	240

Duncan Grouping	Mean	Time (min)
A	56.9608	2
A	56.2692	1
B	55.0067	3
C	52.8133	4

II-G. ANOVA tables and mean separation for redness values of the baked chicken nuggets

Dependent Variable: Redness (a values)
ANOVA table for the effect of the baking treatments on redness (a values)

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	117.7970365	9.8164197	23.95	<.0001
Error	91	37.2991125	0.4098804		
Corrected Total	103	155.0961490			

R-Square = 0.759, CV = 5.61

ANOVA table for the effect of time, temperature and their interaction on redness

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	16.85781667	8.42890833	17.51	<.0001
Time	3	19.70035000	6.56678333	13.65	<.0001
Temp*Time	6	20.09455000	3.34909167	6.96	<.0001

R-Square = 0.782, CV = 6.11

Duncan Grouping	Mean	Temp (°C)
A	11.9600	240
A	11.5688	220
B	10.5538	200

Duncan Grouping	Mean	Time (min)
A	12.2900	4
B	11.6225	3
C	10.7858	2
C	10.7450	1

II-H. ANOVA tables and mean separation for yellowness values of the baked chicken nuggets

Dependent Variable: Yellowness (b values)
ANOVA table for the effect of the baking treatments on yellowness (b values)

Source	DF	SS	Mean Square	F Value	Pr > F
Treatment	12	589.9319962	49.1609997	49.56	<.0001
Error	91	90.2702375	0.9919806		
Corrected Total	103	680.2022337			

R-Square = 0.867, CV = 2.25

ANOVA table for the effect of time, temperature and their interaction on yellowness

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Temp	2	80.95765417	40.47882708	30.46	<.0001
Time	3	79.02235000	26.34078333	19.82	<.0001
Temp*Time	6	43.39496250	7.23249375	5.44	0.0005

R-Square = 0.823, CV = 2.63

Duncan Grouping	Mean	Temp (°C)
A	45.2106	220
B	44.2463	200
C	42.1031	240

Duncan Grouping	Mean	Time (min)
A	45.1067	2
A	44.9567	1
B	43.3892	3
C	41.9608	4