QUALITY CHANGES IN CHICKEN NUGGETS FRIED IN OILS WITH DIFFERENT DEGREES OF HYDROGENATION

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ABSTRACT

The goal of this research was to investigate the influence of the degree of hydrogenation of frying oil on quality and textural changes in chicken nuggets during deep-fat frying. Thermal stabilities of the frying oils were also studied. The frying oil consisted of blends of hydrogenated and non-hydrogenated oils mixed at different ratios. Physical and textural attributes of the products, as well as the moisture and fat contents, were measured at various frying times. Oil samples were withdrawn at different times and analyzed for colour, free fat acid (FFA) content, viscosity and dielectric properties. Physical and textural properties of chicken nuggets were influenced by frying time and the degree of oil hydrogenation. The experimental data, for changes in the properties of both frying oil and fried product, was adequately described using first order reaction kinetics. Increasing frying time decreased product lightness whereas chroma and hardness values increased. Frying in oils with higher degrees of hydrogenation resulted in products with lighter and harder (more crispy) texture. Products fried in non-hydrogenated oil absorbed more oil but also retained more moisture compared to samples fried in hydrogenated oil. The rate of change in the colour parameters of oils was observed to increase with increasing frying time and the degree of hydrogenation. The chroma values of the oils increased when frying time increased and degree of hydrogenation decreased. The viscosity of oil tended to increase with increasing degree of hydrogenation. The FFA content and dielectric constant of the frying oils correlated with frying time and degree of hydrogenation.

RÉSUMÉ

Nos recherches visèrent à évaluer l'influence du degrée d'hydrogénation de l'huile de cuisson sur la qualité et le changement de texture de pépites de poulet préparées en grande friture. La stabilité thermique des huiles fut également étudiée. Une gamme d'huiles de cuisson fut préparée en mélangeant selon différents rapports des huiles hydrogénées et non-hydrogénées. Les caractéristiques physiques et texturales du produit, ainsi que sa teneur en eau et en gras furent mesurées après différentes durées de cuisson. Des échantillons d'huile furent prélevés à divers moments de la friture, et leur couleur, teneur en acide gras libres, viscosité et propriétés diélectriques furent évalués. Les caractéristiques physiques et texturales des pépites de poulet furent influencées by la durée de friture et par le degré d'hydrogénation de l'huile. Les données expérimentales de changements des propriétés de l'huile de cuisson et du produit frit, furent adéquatement décrits par un cinétique de premier ordre. Une augmentation de la durée de friture réduisa la clarté du produit, tandis que son chroma et sa dureté augmentèrent. La friture dans une huile dont le degrée d'hydrogénation était plus élevé donna lieu à un produit d'une plus grande clarté et dont la texture était plus dure (croquante). Le produit frit dans une huile relativement non-saturée imbiba plus d'huile, mais demeura d'une teneur en eau plus élevée, que celui frit dans une huile plus saturée. Le taux de variation des paramètres de couleur des huiles augmenta avec la durée de friture, ainsi qu'avec le degré d'hydrogénation. Les valeurs de chroma des huiles augmentèrent avec la durée de friture, et diminuèrent avec l'augmentation du degré d'hydrogénation. La viscosité de l'huile eut tendance à augmenter avec le degré d'hydrogénation. La teneur en acides gras libres et la constante diélectrique des huiles de friture fut corrélé avec le temps de friture et le degré d'hydrogénation.

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1. a table of contents;
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3. an introduction which clearly states the rational and objectives of the research;
4. a comprehensive review of the literature (in addition to that covered in the introduction to each paper);
5. a final conclusion and summary;
6. a thorough bibliography;
7. Appendix containing an ethics certificate in the case of research involving human or animal subjects, microorganisms, living cells, other biohazards and/or radioactive material.

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NOMENCLATURE

A	The cross-sectional area
a^*	Colour index (redness or greenness)
a^*_{st}	Standard colour index of redness
AOCS	American Oil Chemists' Society
ANOVA	Analysis of variance
atm	Atmosphere
b^*	Colour index (yellowness or blueness)
b^*_{st}	Standard colour index of yellowness
$C*$	Colour index (chroma)
cis	*Cis*-fatty acid
CHD	Coronary heart disease
db	Dry basis
DFF	Deef-fat frying
DSC	Differential scanning calorimetry
ΔE	Total colour difference
FFA	Free fatty acid
h^o	Colour index (hue angle)
L^*	Colour index (lightness)
L^*_{st}	Standard colour index of lightness
MC	Moisture content
nm	Nanometer
OC	Oil content
ppm	Part per million
psig	Pounds per square inch, gauge
TAG	Triglyceride
TPM	Total polar material
trans	*Trans*-fatty acid

Greek

γ	The shear rate
μ	Viscosity
σ	Shear stress
κ	Reaction rate constant

I. GENERAL INTRODUCTION

1.1 INTRODUCTION

Fried foods have continued to be popular in spite of the current guidelines which recommend a decrease in the content of fat in our diet (Dobarganes et al., 2000). Frying is a fast and convenient technique for production of foods with unique sensory properties including colour, flavor, texture, and palatability that are highly appreciated by consumers. Therefore, it is important to understand the frying mechanism in order to manufacture, preserve, and market fried foods optimally (Moreira et al., 1999).

Deep-fat frying is a process in which the food is cooked by immersion in hot oil. Despite the fact that the Deep-fat frying industry is well-established and highly automated, the deep-fat frying process is considered to be an art rather than a science (Blumenthal, 1991). It is a complex process. During deep frying, thermal, oxidative, and hydrolytic reactions take place resulting in physical and chemical changes in the oil and the formation of new compounds. The oils used in Deep-fat frying are usually blends of partially hydrogenated animal fats and vegetable oils (Brooks, 1991). Many researchers, such as White (1991), Blumenthal (1991), Walter and Serbia (1991), Pinthus et al. (1995), investigated chemical changes of frying oils during frying and the effect of these degenerative by-products on oil quality. Fried foods absorbe the degraded oil, which contribute to their low quality (Dobarganes et al., 2000).

Nowadays, health factors are critical in evaluating food products. There is interest in lowering the oil content in fried foods. Several researchers have made substantive attempts to understand the different aspects of Deep-fat frying process including pore development (Kassama and Ngadi, 2000), heat and mass transfer (Ateba and Mittal, 1994; Moreira et al., 1995; Rice and Gamble, 1989). In addition, new frying processes and equipment have been invented to improve product quality, save energy and increase the health factor of fried foods.

This study was designed to evaluate changes in colour, texture, oil and moisture content of chicken nuggets fried in oil blends consisting of different proportions of hydrogenated and non-hydrogenated oils. The stability of oils was also investigated by monitoring changes in the oil properties with frying time.

1.2 HYPOTHESIS

The hypothesis of this study is that frying with oils containing different proportions of hydrogenated and non-hydrogenated canola oil will influence the quality of fried chicken nuggets. It is assumed that the hydrogenated and non-hydrogenated oils contain no impurities that should affect frying product quality.

1.3 OBJECTIVES

Based on the hypothesis, the objectives of this study can be grouped into two:

1. To evaluate the physical and textural characteristics such as surface colour, texture, oil and moisture content of chicken nuggets fried in oils of different degrees of hydrogenation.
2. To study the thermal stability of blends of hydrogenated and non-hydrogenated oils during deep-fat frying.

1.4 SCOPE

This study was based on chicken nuggets. Applied methods and treatments can be applicable to other fried foods, but proper research must be done with the intention of determining appropriate conditions. Every fried food has its own characteristics, and thus must be subjected to each suggested method.

II. REVIEW OF LITERATURE

2.1 DEEP-FAT FRYING

Frying is a fast and convenient technique widely used in industrial, catering and domestic cooking processes. The popularity of frying is related to the unique sensory properties of fried food, especially colour, flavor, texture and palatability, which are highly appreciated by consumers. In frying, foods are submerged in oil heated in the presence of air. The oil is exposed to the action of four agents which cause drastic changes in its structure: (1) moisture from the food, giving rise to oxidative alteration; (2) atmospheric oxygen entering the oil from the surface of the container, giving rise to oxidative alteration; (3) the high temperature at which the operation takes place (about 190°C) which results in thermal alteration, and finally (4) contamination by food ingredients (Moreira et al., 1999).

Gertz (2000) summarized changes in properties and frying by-products of frying oils and fats (Figure 2.1). During the frying process, there are four distinct stages: (1) heat-up period, (2) surface boiling period, (3) falling rate period, and (4) bubble end point. The first and the fourth stages may be generalized as non-boiling phases, while the second and the third stages are boiling phases. Deep-fat frying normally includes several aspects:

1. Mass transfer: Water in a frying food migrates from the center to the surface. As water is removed at the surface due to heating, water is transferred to the surface. The rate of water loss and its ease of migration through the product are important to the final characteristics of the food. Ngadi et al. (1997) modeled moisture transfer during deep-fat frying of chicken drumstick. The region of rapidly decreasing moisture content at the surface of the chicken drumstick was identified. That region starts on the surface at the onset of frying then it extends into the inner parts of the drumstick. 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.

2. Heat transfer: Water evaporation from the surface of a frying food also removes heat and inhibits charring or burning at the surface. The heat of vaporization of water to steam removes much of the heat at the food/oil surface.

3. Heat removal: As long as water is being removed at a sufficient rate, the surfaces of the food will not char. Subsurface water in the food will also conduct heat away from the surface and towards the center of the product.

4. Interior cooking: The transfer of heat to the interior of the product by water will result in cooking of the interior of the food.

5. Oil-food interactions: Ideally, the food products should have similar dimensions and thus, similar surface to volume ratios. Once equilibrium is established all processes should be the same unless there are changes in equipment function or in oil composition.

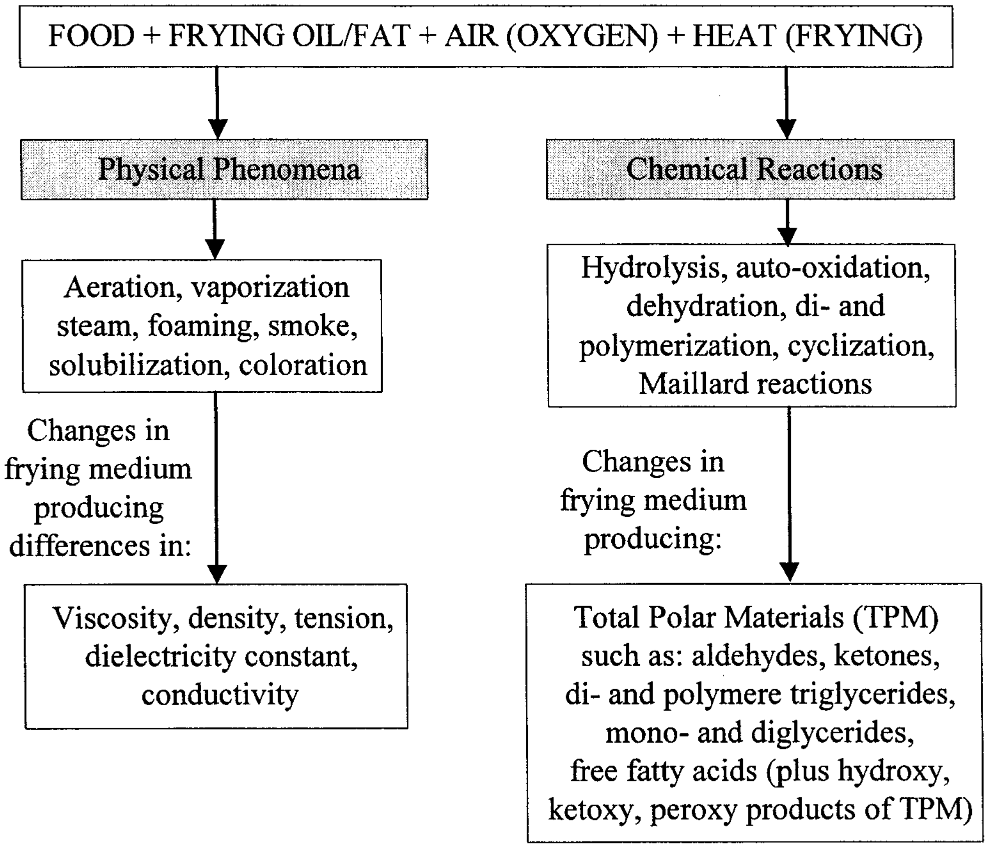

Figure 2.1 Changes in physical and chemical properties of frying oils and fats during frying of foods (Gertz , 2000)

2.2 FRIED FOODS QUALITY

Food quality is the sum of all the desirable characteristics that make a food acceptable to eat. Quality characteristics of a product may be divided into three major categories: sensory, hidden and quantitative (Salunkhe et al., 1991). The sensory characteristics are colour, gloss, size, shape, defects, odor and taste. Hidden characteristics are nutritive value, presence of dangerous contaminants and poisonous materials. Quantitative parameters are those that contribute to overall food quality. Brückner and Auerswald (2000) and Bourne (1982) reported texture, appearance and colour to be the most important properties since they are directly perceived by the senses.

In general, the frying industry controls product quality by product appearance and flavor. These quality characteristics can be determined by measuring the related product properties, including: moisture content, colour, flavor, texture, yield, nutrition and shelf life stability. Not all fried foods are checked on the same quality standards (Moreira et al., 1999). For fried chicken nuggets, surface appearance and texture are the most significant factors for acceptability.

2.2.1 Sensory evaluation

Colour is one of the first noticed characteristics of food, and formerly it was evaluated only subjectively or with use of colour comparing charts. The most common technique to assess colour is by the colorimeter. There are several colour scales in which the surface colour can be represented. The 3-dimensional scale L*, a* and b* mimic the perception of colour by the human eye, and defines colour appearance in a way that can be readily understood. The L^* is lightness coefficient, ranging from 0 (black) to 100 (white) on a vertical axis. The a^* is purple-red (positive a^* value) and blue-green (negative a^* value) horizontal axis. Second horizontal axis is b^*, that represents yellow (positive b^* value) or blue (negative b^* value) colour (McGuire, 1992).

Figure 2.2 depicts the 3D colour system in graph. The values of L^*, a^* and b^* can be converted to hue angle (h^o) and Chroma (C^*) value, analogous to colour saturation or intensity (McGuire, 1992). Colour difference ΔE can be calculated if one wants to find the difference between the sample and a previously chosen standard (McGuire, 1992).

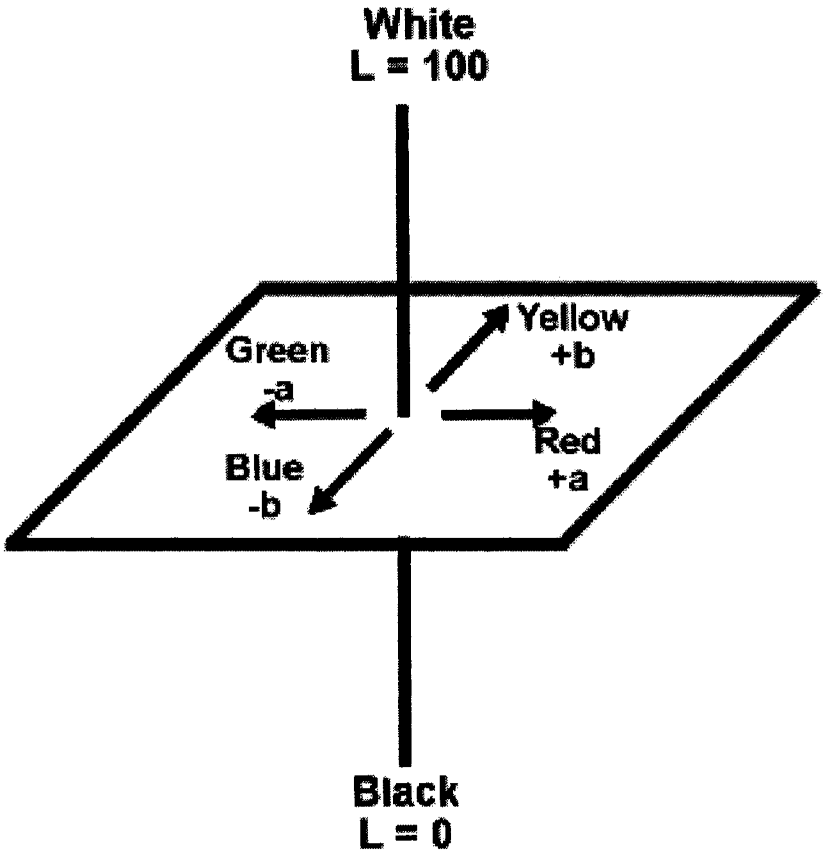

Figure 2.2 $L^*a^*b^*$ **colour three-dimensional system (HunterLab, 1996)**

The colour can be calculated according to the below formula:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{2.1}$$

Where:

$$\Delta L^* = L^* - L^*_{st} \tag{2.2}$$

$$\Delta a^* = a^* - a^*_{st} \tag{2.3}$$

$$\Delta b^* = b^* - b^*_{st} \tag{2.4}$$

L^*_{st}, a^*_{st}, and b^*_{st} are Hunter values of the standard. (McGuire, 1992)

2.2.2 Texture characteristics

Textural quality, i.e. the way a food feels to the tongue when eaten, is another important attribute for the acceptability of fried foods (Medved, 1986). The crust will form as a result of dehydration and reactions between amino acids, carbohydrates, lipids and their breakdown products. Crusts cook faster than the interior of some products during high-temperature frying. Upon frying, the crispness of chips increased as the porosity increased and moisture decreased (Kawas and Moreira, 2001).

Texture analysis is primarily concerned with the evaluation of mechanical characteristics where food is subjected to a controlled force from which a deformation curve of its response is generated. These mechanical characteristics can be further sub-divided into primary and secondary sensory characteristics. Both hardness (soft, firm, hard) and viscosity (thin, viscous) belong to the primary sensory characteristics.

Textural characteristics can be measured by any standard procedure. The type and force direction can be different, depending on method applied. In the 1960's scientists also began using the Instron Universal Testing Machine. A full range of test probes and fixtures have also been developed to allow testing a wide range of food products.

When analyzing texture, it is generally necessary to test a number of pieces and determine the average values to obtain a representative result. The Instron testing machine, which is usually used to determine food texture, can be classified as simple compression or stress relaxation. It offers different probes for different foods and the test results can be depicted in a texture profile analysis (TPA) graph.

2.2.3 Oil and moisture content

Oil absorption is essentially a quantitative water replacement process. Oil absorption is a complex phenomenon that happens mostly when the product is removed from the fryer during the cooling stage (Sun and Moreira, 1994).

Baumann and Escher (1995) found that varying frying oil temperature under atmospheric conditions caused a slight increase in the final oil content of chips. Oil uptake has a tendency to increase with frying temperature and time (Krokida et al., 2000, 2001c; Gamble et al., 1987). Higher oil temperatures result in a faster development of a solid crust and consequently surface properties that are favourable for oil absorption. In the case of frying under vacuum, the final oil content of potato chips is not a function of oil temperature, but depending on frying time (thus remaining moisture), which increases with decreasing oil temperature (Krokida et al., 2001c).

The moisture loss kinetics are based on the following relationship:

$$\frac{d(x)}{dt} = -k_x(x - x_e) \tag{2.5}$$

Where x is moisture content at anytime t, x_e is the moisture content at an infinite process time (kg/kg wb), and k_x the rate constant of moisture uptake (s^{-1});

The oil uptake kinetics are based on the following:

$$\frac{d(c)}{dt} = k_c(c - c_e) \tag{2.6}$$

Where c is fat uptake at anytime t, c_e is the fat uptake at an infinite process time (kg/kg db), and k_c the rate constant of fat/oil uptake (s^{-1}).

Integrating Eq. (2.5) and (2.6), yielded Eq. (2.7) and (2.8), as follows:

$$\frac{x - x_e}{x_0 - x_e} = \exp\left(-k_x t\right) \tag{2.7}$$

$$\frac{c - c_e}{c_0 - c_e} = \exp\left(-k_c t\right) \tag{2.8}$$

Where x_0 are moisture contents at time zero (Eq. 2.7), while oil uptake at time zero was assumed to be zero as shown in Eq. (2.8).

Kinetic analyses have indicated that the rate of oil uptake increases with temperature. Based on the capillary theory of drying, water in the sample vaporizes, and subsequently creates capillary pathways, thus enabling oil uptake to occur (Guillaumin, 1988). This was evidenced by the high correlation between moisture loss and fat uptake. Despite efforts to study the mechanisms and control oil uptake (Moreira et al., 1997; Saguy and Pinthus, 1995; Ufheil and Escher, 1996), most fried foods contain significant amounts of oil.

2.3 FACTORS INFLUENCING FOODS QUALITY DURING DEEP-FAT FRYING

Many factors can affect the quality of the final fried food. Fried food quality is not only related to the quality of raw materials (foods, frying oil) but also frying temperature, frying duration, processing method, food pretreatment, food geometry, fryer, etc. Some of these factors will be discussed in this section.

Process variables, such as oil temperatures, oil types and sample dimensions, are expected to affect the colour of fried products (Krokida et al., 2001b). However, the effect of oil type on a^* parameter is negligible, as well as the effect of oil type on oil content (Krokida et al., 2000). Oil types also apparently affect density, which is higher for 100% hydrogenated oil (Krokida et al., 2000).

Frying conditions can significantly affect the texture properties of fried foods, for example crispness. Krokida et al. (2001a) reported that the oil type affects significantly potato crispness (maximum stress to maximum strain ratio), more specifically the use of hydrogenated oil instead of cottonseed oil increased potato crispness. However, there are no significant effects detected in terms of oil type on water loss of fried potatoes (Costa and Oliveira, 1999).

2.3.1 Frying temperature

The normal temperature range for food service frying is 160 to 190 °C. However, higher temperatures of 190 to 205 °C are also used in frying process (Dunford, 2004). Most foods cook rapidly in the 160 to 190 °C range and develop a golden colour, crisp texture and good flavor. The products fried in the normal temperature range absorb 8 to 25 percent oil. Frying time is longer at lower temperatures.

Frying at lower temperatures results in lighter colour, less flavor development and increased oil absorption. High-temperature frying leads to thinner crusts and less oil absorption. Crusts cook faster than the interior of some products during high-temperature frying. In such cases, crusts usually have to be over fried in order to get the interior cooked properly (Dunford, 2004).

In batch frying, the temperature of the oil decreases by about 30 to 40 °C when the product is added to the fryer. The temperature decrease can be higher for frozen foods. The guideline is that temperature of the oil should recover to its set point at least by the end of the frying cycle so that the fryer will be ready to fry the next batch. Oil oxidizes faster at higher temperatures. For example, increasing the frying temperature from 163 to 180 °C more than doubles the oxidation reaction rate; therefore, frying temperature, even within the normal range, should be selected very carefully. The midpoint of the normal frying range, 176 °C, is a good starting point to establish the frying temperature for a new product; however, any frying temperature that achieves the best flavor, texture and eating qualities for the product should be used.

Oil temperature during deep-fat frying alters the physiochemical properties and microstructure of the food products due to different degrees of thermal gelatinization of starch in potato products and denaturation of protein in meat products over a given period of time. Diaz et al. (1999) reported that temperature had little effect on fat content during frying of plantains (a kind of banana) 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). High frying temperature can also result in the formation of undesirable compounds due to the interaction of oil and water (Blumenthal, 1991; Fritsch, 1981) and affects the viscosity. For example, Singh (1995) reported that the kinematic viscosity of corn oil increased from 2.65 to 3.28 mm^2/s as oil thermally degraded. Kassama and Ngadi (2000) reported a substantial increase in oil uptake at higher frying temperature due to lower viscosity.

An increase in temperature dramatically raises the rate at which fatty acids react with oxygen, promoting rancidity, and therefore increasing the peroxide value. Increasing the frying oil temperature tends to decrease oil uptake because the product spends less time in the fryer. It might be that this process is aided by the formation of a crust that acts as a barrier to further oil uptake. In addition, it might prevent water from leaving the food to an extent and consequently hinder the ingress of oil. However, it is important to find the optimum frying temperature to prevent a semi-raw and oily product as a result of too low a cooking temperature and a burnt and only partially cooked product from too high a frying temperature (Gertz, 2000).

2.3.2 Food pretreatment

Batter coating and breaded coating are two prominent fried food pretreatment methods all over the world, which produced fried foods with a crispier texture, more desirable colour and flavor, improved nutritional value and contributed to the eating pleasure. Batter and breading are also the most commonly used methods to treat meat foods. Fried chicken products exceeded $8.2 billion in sales in the US in 1996 (*source:* Tricon 1997 Annual Report). Chicken nuggets, as well as other breaded foods, are coated with a batter-breading layer that acts as a barrier to moisture loss and a carrier of spices and other ingredients for flavor enhancement. It was suggested that Deep-fat frying results in better quality of prepared nuggets compared to other cooking methods (Yoon et al., 1999).

The breading materials commonly consist of breadcrumbs, corn meal, cracker meal, and various prepared breading mixes. The batter, generally has an egg-milk base, is used to moisten the product so that the breading will adhere properly. The high-protein batter-breaded chickens have apparently improved texture (Kadan et al., 1997; Moreira et al., 1999). Furthermore, batters containing pregelatinized corn flour produce coatings with high moisture content and little oil absorption, resulting in a crispier product.

The formation of a surface crust is helped by the presence of starch. The crust generally should be a barrier to the mass transfer of oil to fried food (water discharge and fat uptake), but many other factors (increased food surface, development of heat transfer and relative cooking time, etc.) can modify the crust's fat absorption capacity. Battering reduces oil uptake and water loss. A clear-coat batter should be rather invisible but have high functionality, a low batter pick-up during coating and a significantly improved crispiness after deep-fat frying.

2.3.3 Frying oil

Oils and fats are used as a means of heat transfer from the fryer to the food. The quality of oils and fats during the frying process has a major influence on the quality of the final product. It is important to understand the oil degradation process and control the oil quality to produce high quality fried foods.

Robertson (1967) proposed several basic guidelines for assuring the quality of fried foods. In his eight basic criteria, monitoring chemical indices of oil degradation, keeping salt and other sources of metal from oil and filtering oil regularly are closely related with the quality of frying oil. Brinkmann (2000) also proposed several quality criteria for industrial frying oils and fats as well as optimum frying conditions. However, the aforementioned beneficial effects of frying are accompanied by undesirable alterations of the frying medium. Thermal treatment of the cooking oils results in oxidative and hydrolytic reactions. Chemical and physical changes also take place resulting in the formation of undesirable secondary products (Fritsch 1981; Friedman 2000; Gertz 2000) which resulted in poor quality fried foods.

The quality of the frying medium and of the food fried in that oil is intimately related (Blumenthal, 1991). Foods and oil quality should be closely monitored regardless of the industrial operation or home cook. The frying oil should be discharged before it begins producing unacceptable foods. Oil quality may be influenced by the nature of the food fried, especially when the product introduces foreign oils, emulsifiers, trace metals, food scraps, free fatty acids, alkaline-reacting material or other components into the frying oil. In deep-fat frying, oil degradation accompanied with thermal oxidation, polymerization, hydrolysis, and the resultant decomposition products adversely affected the flavor and colour offered by food products (Clark and Serbia, 1991; White, 1991; Tyagi and Vasishtha, 1996). The rate of decomposition depends on the composition of the oil, the temperature and length of frying, whether continuous or intermittent frying is used, the type of food fried (e.g. its moisture content), and whether or not fresh oil is added to replenish the frying oil (Paul and Mittal, 1996). In addition, undesirable constituents produced from degraded frying oils may even be harmful to health. Among these factors, the degree of unsaturation of the oil is the most important factor influencing the frying stability of the oil. Blumenthal (1991) explained oil degradation and the effect of the oil on the food from engineering aspects of oil degradation to oil chemistry aspects.

Frying oil quality has also a certain influence on oil absorption and therefore on the organoleptic and nutritive characteristics of fried food products. That is attributed to formation of oil degradation compounds (high molecular weight polar compounds) that increased the polarity of the frying medium. Consequently, the oil viscosity increased which farther increased the amount of oil on the food surface (Alim and Morton, 1974; Orthoefer and Cooper, 1996). On the other hand, the interfacial tension between the food and the oil would decrease and in this way facilitate oil absorption (Dobarganes et al., 2000). Increasing the concentration of hydrogenated oil in the frying medium does not significantly affect mass transfer during frying. Water loss and oil uptake phenomena are getting more intense at higher temperatures and smaller sample thickness (Krokida et al., 2000).

Oil turnover is defined as the ratio between the amount of oil in the fryer and the amount of oil consumed per hour. Frying oil turnover is an indicator of how much stress the oil is subjected to in a daily operation. Oil turnover in hours for a food service operation is defined as:

$$\text{Oil turnover} = \frac{\text{Total weight of oil in the fryer}}{\text{Average weight of oil used per hour}} \tag{2.9}$$

2.4 CHEMISTRY OF FRYING OIL

2.4.1 Type of frying oil

Frying oils can be classified according to different standards. According to the oil origin, oil can be classified into plant oil and animal fat. The most commonly used oils are peanut oil, sunflower oil, coconut fat, clarified butter, olive oil and canola oil. The properties of oil change with frying. The ideal oil quality is achieved at break-in (Table 2.1). However, extended use exposes the oil to diffused water, heat, light, and oxygen, which react with the triglycerides to form free fatty acids, polar and non-polar compounds and alkaline soaps as shown in Table 2.1. As the concentration of these materials increases, many physiochemical properties of the oil change, such as, viscosity, thermal conductivity, dielectric properties, specific gravity, specific heat capacity, surface tension and interfacial tension.

The classification of fats and oils vary according to their end use. For shortenings and margarines, fats may be classified by fatty acid chain lengths, degree of unsaturation, dominant polymorphic form, source, consumption, and those fatty acid species that dominate that particular fat (Ghotra et al., 2002). The ACOS (American Oil Chemists' Society) classify frying oils into 6 categories according to their different physical chemical properties and functions (Table 2.1).

Table 2.1 Deep-fat frying oil quality parameters: phases oil passes through during the degradation process

Oil quality (%)	Triglycerides	Polar Compound	Polymers	FFA	Oxidized fatty acids	Soaps (ppm)
New oil	>96	<4	0.5	0.02	0.01	0.7
Break in	90	10	2.0	0.50	0.08	10.0
Fresh	85	15	5.0	1.00	0.20	35.0
Optimum	80	20	12.0	3.00	0.70	65.0
Degraded	75	25	17.0	5.00	1.00	>150.0
Runaway	65	35	25.0	8.00	2.00	>200.0

Source: Blumenthal, M.M. and R.F. Stier (1991)

2.4.2 Chemical composition of oil

Both fats and oils have the same general chemical structure. They differ only in their melting point. A fat has a melting point above room temperature, while an oil has a melting point below room temperature. Fats and oils carry flavor, odor and fat-soluble vitamins. They all have different functional and sensory characteristics.

Fats and oils consist to a large extent of triglycerides that are three fatty acid molecules joined by glycerol (Stockwell, 1988) and are hydrophobic substances (Kalapathy and Proctor, 2000). The esterification of glycerol combined with fatty acids forms mono-, di-, and triglycerides. The different oils and fats differ in the size of their individual fatty acids and, in the degree to which they are unsaturated (Campbell et al., 1999). This affects their physical properties including melting point. For frying oil, its properties are dictated by the actual fatty acids that are present in the individual triglyceride molecules. Some of these components of fatty acids are longer or shorter in chain length than others.

$$\begin{array}{l} CH_2OCOR \\ | \\ CHOCOR \\ | \\ CH_2OCOR \end{array} \qquad \begin{array}{l} CH_2OCOR_1 \\ | \\ CHOCOR_2 \\ | \\ CH_2OCOR_3 \end{array}$$

a. Triglyceride with the same fatty acid groups b. with the different fatty acid groups

Figure 2.3 Structure of triglyceride

Most vegetable and animal fats contain fatty acids with a length of 14 to 22 carbon atoms. The numbers of double bonds and their arrangement styles also have substantial effects on the physiological properties of the different dietary fats and oils. The more double bonds the fatty acids of a triglyceride contain, the lower their melting point. For example, most vegetable triglycerides with a lot of double bonds are oils, whereas the animal triglycerides, with few double bonds, tend to occur in the form of hard fats. By removing the double bonds (hydrogenation), the oily vegetable products can be converted into hard fats.

Fatty acids with no double bond are referred to as saturated, those with one double bond are monounsaturated; and those with more than one double bond are polyunsaturated. The stability of the oil depends on the molecular structure of these bonds.

2.4.3 Nutritive value of oil

Fats and lipids are vitally important elements of our diet that aid in the absorption of the fat-soluble vitamins (A, D, E, and K), supply essential fatty acids and provide energy reserves, insulation, and protection of sensitive organs (e.g. kidneys) (Giese, 1996). It is recommended that at least 15% to 20% of adult calorie intake and at least 30% to 40% of infant calorie intake consist of fat. Fats and oils are the primary components of products such as margarines, shortenings, butterfat, fried foods, mayonnaises, salad dressings, baked products, infant formulas, snack and confectionery products, etc.

Fats and oils supply the body with highly concentrated energy. One gram of fat supplies approximately 9 cal of energy. That is more than twice as much as the energy contained in proteins and carbohydrates (at 4 cal/gram) (Giese, 1996). Fat is therefore the best form of energy storage. Fat is also a carrier for flavors. Dietary lipids include cholesterol and three kinds of fats: saturated, polyunsaturated, and monounsaturated fatty acids. Oil consumption, especially saturated fat, is recognized as one of the major factors playing a significant adverse role in health hazard (e.g. coronary heart disease (CHD), cancer, diabetes, hypertension) (Saguy and Dana, 2003).

Vegetable fats such as grain, seed, and nut oils tend to be less saturated and less harmful than animal fats such as butter and lard, but they are equally calorie-dense. Research has proven that polyunsaturated fats help the body get rid of newly formed cholesterol and reduce cholesterol deposits in artery walls. Monounsaturated fats also reduce blood cholesterol, but only when the overall diet is very low in saturated fat.

2.4.4 Hydrogenated oil

Hydrogenation of vegetable oils was first used in Europe in the early 1900s and introduced in the US in 1910 by Procter and Gamble. Hydrogenation or the hardening process is a saturation process. The main objectives of hydrogenation are to convert liquid vegetable oils into plastic and to improve the oxidative stability and therefore the flavor and shelf-life of liquid vegetable oils. Furthermore, hydrogenation can also change melting characteristics and behaviors of oils and improve colour.

In the case of complete hydrogenation, unsaturated fatty acids present in the original oil are converted entirely into the corresponding saturated acids. Thus, this process maintains the organoleptic characteristics of oils for longer shelf life. In the process of hydrogenation, carbon-carbon bonds are substituted by hydrogen-carbon bonds. This process is usually conducted after bleaching. The catalyst used in hydrogenation of most vegetable oils is nickel, supported on a highly porous inert material, such as silica or alumina. Hydrogenation is typically conducted at 150°C to 200°C and the pressure of hydrogen gas is ranging from 0.8 atm (10 psig) to 4.0 atm (60 psig) (Hernandez, 2002).

Fully hydrogenated oil is obtained when all the double bonds are saturated; otherwise the oil is referred to as partially hydrogenated oil. Factors that affect the hydrogenation process and consequently the resultant products, are the temperature of the oil mixture, hydrogen gas pressure, catalyst activity, catalyst concentration, agitation of the mixture, and time duration of the process (Chrysam, 1985; Coenen, 1976).

Animal fat is composed primarily of short chain fatty acids (<C14), which are mostly saturated fatty acids. They are naturally solid at ambient temperature (25 °C). In contrast, unsaturated vegetable oils have a bend or crook in the base carbon chain where the double bond occurs (*cis*-unsaturated fatty acids). These bends or crooks tend to keep the fatty acid molecules from lying closely together and the compounds remain liquid at ambient temperature. When vegetable oils are hydrogenated, some unsaturated bonds remain, but the geometry of the unsaturated carbon-carbon bonds is changed from "*cis*" to "*trans*". Trans fatty acids can lie parallel to each other, allowing the oils to act like fats and become solid at lower temperatures.

Hydrogenated fats and oils are dangerous for human health. They can raise cholesterol levels, increases the risk of coronary heart disease, so it should be omitted completely from a healthy diet because of their unnatural content of harmful trans-fatty acids and traces of metallic nickel which function as a catalyst in the hydrogenation process.

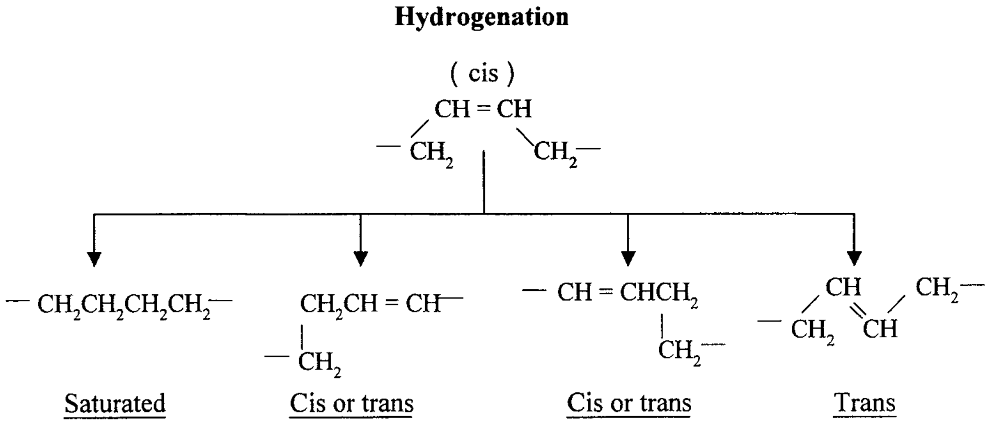

Figure 2.4 Hydrogenation process

2.4.5 Non-hydrogenated oil

Compared with hydrogenated oil, oils and fats without undergoing artificial hydrogenation process are called non-hydrogenated oil. All naturally occurring unsaturated oils have a *cis* arrangement around the double bond. Without hydrogenation, many vegetable oils lack the necessary stability to be used in food processing. Foods using unsaturated vegetable oils in their natural state would have a shorter shelf life, could oxidize and become rancid more quickly and would not have the same consistency. The rate of oxidation can be linked directly to type and extent of unsaturation. C18:3 linolenic acid with its two reactive methylene groups (at C11 and C14) is 200 times more prone to oxidation and the development of off-flavors than C18:0 stearic (Thomas,1998). Hence, hydrogenation can produce the more stable linoleic or oleic acid. In industrial frying oils, the level of polyunsaturates must be low, and in particular the level of C18:3 should be less than 1% or lower, if performance and shelf life requirements are to be met.

Table 2.2 Oxidative stability

Oxidation rate linked to unsaturation
C18:0 = 1
C18:1 = 10
C18:2 = 100
C18:3 = 200
C18:3 (c,t,t) = 800

2.5 QUALITY PROPERTIES OF FRYING OIL

Oil is primarily the medium of heat transfer in deep-fat frying, so oil properties play an important role in affecting the frying process. Continuous use of frying oil will change the physical, chemical and thermal properties of oils 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).

Liquid frying fats are popular due to their convenience in handling. They range from clear to opaque fluids at room temperature, e.g. soybean, canola and palm oil. Based on the specific requirements of a product, such as appearance, seasoning adhesion, mouth-feel, fat retention and shelf period, different frying oils are selected (Dunford, 2004).

Indicators to evaluate frying oil quality normally include total polar compounds, conjugated dienes, free fatty acid (FFA), dielectric constant, colour, viscosity and pH. Apart from these parameters, there are still other characteristics to evaluate the frying oil quality, for example plasticity, crystallization properties, odor and oiliness.

2.5.1 Oil colour

In the oil production process, there is a process called bleaching, the major purpose of which is to remove the undesirable colour materials from oil. Heated oil (about 85°C) may be treated with various bleaching agents, such as activated carbon or activated clays. Many impurities, including chlorophyll and carotenoid pigments, are adsorbed onto such agents and removed by filtration. People often connect the dark colour of frying oils with bad or dark coloured foods. Normally, liquid oils have a yellow colour and solid fats are white and opaque. Different oil and fats have exiguous differences based on the oil origin and treatment process. The colour of frying oil will affect the colour of fried foods, and it can also used to judge the frying time.

Deteriorated oil has apparent signs that can give you a sensory judgment. Changes in the colour of oils during frying are a complex process. Oil components, such as pigments, and foods are the main causes of oil darkening. When subjected to high/prolonged heat, oil colour will darken. The Lovibond method (AOCS Cc 13E-92) is the standard colour method for measuring the colour of refined oils and melted shortenings. A visual match is made between the sample and colour filters with varying indexes of red and yellow colour. Researchers may want to use Lovibond Red, Yellow, and Blue in frying work (Stier and Blumenthal, 1993). However oil colour has not been found to be an effective index for oil quality or for discard. It is too subjective and bears no relation to the ability of that oil to produce quality food, although many do use it.

2.5.2 Relative viscosity

Viscosity is a more important factor for evaluating the quality of frying oil. The viscosity of both oil and fats are greater than water. With increasing length of fatty acid chain in fats/oils, viscosity increases. With increasing of the amounts of unsaturated fatty acid, the viscosity decreases. Viscosity decreases as temperature increases, but heating over a long period can result in an increase in viscosity. However, the extent of the change of each physical property during heating up depends on the nature of the oil. Saturated fats show a higher viscosity than unsaturated oils.

The longer you use an oil, the higher its viscosity becomes due to changes in the oil's molecular structure. The viscosity of oil increased as the oil degraded. Therefore, it can be regarded as an indicator of the deterioration level of oil (Tseng et al., 1996).

Oils, whether fresh or degraded, behaved as Newtonian fluids (Tseng et al., 1996). They exhibit a linear relationship between shear stress and shear rate according to the following equation:

$$\sigma = \mu \times \gamma \tag{2.10}$$

Where σ is the shear stress, γ is the shear rate and μ is the viscosity (Moreira et al., 1996).

However, There are different opinions on oil viscosity. Gómez-Cuadras et al. (2000) think that the frying oil started to behave as a Non-Newtonian fluid after 6 hours of reheating. Kassama and Ngadi (2002) regard that all grades of oil exhibited a non-Newtonian or pseudoplastic behaviour within the temperature range of 10 to 40°C, while at above 50°C, they behaved as a Bingham fluid.

Viscosity was significantly affected by oil degradation time and temperature, which might facilitate the process of oil uptake. The effect of temperature on the viscosity of the oils was described by an Arrhenius equation. Viscosity changed more rapidly with temperature as the degradation time increased (Tseng et al., 1996). Singh (1995) reported that the kinematic viscosity of corn oil increased from 2.65 to 3.28 mm^2/s as oil thermally degrades.

2.5.3 Heat capacity

The thermal properties of oil play an important role in the effectiveness as a frying medium, which normally include specific heat (C_p) and convective heat transfer coefficient (h).

Heat capacity is an important property of frying oil. It is related to energy consumption. Specific heat is an indicator of heat capacity, i.e. the amount of heat required to increase the temperature of a unit mass of a substance by one degree. It varies with oil degradation. The overall changes in specific heat will depend on the initial quality of oil and the degree of degradation involved. It may also affect oil consumption and frying time. As temperature decreases, the heat capacity will increase.

Specific heat of corn oil was found to decrease significantly (by 14%) after long-time 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. After 30 hours of frying, the change in h values did not decrease significantly; however, after 30 hours of frying a significant change in h values was observed and these values were significant.

2.5.4 Dielectric properties

The dielectric constant is a measure of oil's ability to conduct electric current. Uncontaminated new oil products conduct very little electricity. However, as oil is used, contaminants such as acids, water, food residues enter the oil. All of these contaminants elevate oil's ability to conduct electricity. By monitoring the dielectric property, we can determine the level of contamination within the oil. The utility of the dielectric property has been increasingly recognized as a non-destructible, easy, quick, real time, and continuous method for evaluating changes in foods and biological materials (Klepacki, 1965; Fritsch et al., 1979; Shi et al., 1998). When an oil undergoes thermal and oxidative breakdown, its dielectric constant increases. It is apparent that the dielectric constant increases with increasing heating time correlated with acid value, density, and relative viscosity. The higher the temperature, the faster the dielectric constant increases.

2.5.5 Free fatty acids

Frying oil will break down during food processing. Free fatty acids (FFA) are normally measured to determine the relative stabilities of each oil towards oxidative and thermal deterioration under deep frying conditions. Fatty acids represent an inherent part of the fat molecular structure. During frying, however, they are hydrolyzed from the oil/fat to become FFA. Hydrolysis, a chemical reaction that occurs in the presence of moisture and heat decomposes triglycerides into free fatty acids. This occurs when moisture escapes from the frying food and mixes with the frying oil and elevated temperature stimulate this process. Elevated levels of FFA cause oils to generate smoke during frying, hasten oxidative degradation, and contribute to off-flavors and excessive oil absorption by the food being fried (O'Brien, 1993). Usually the amount of FFA increases with increasing frying time. When the FFA concentration increases, the smoke and flash points of oil decrease.

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III. QUALITY CHANGES IN CHICKEN NUGGETS FRIED IN OILS WITH DIFFERENT DEGREES OF HYDROGENATATION

3.1 ABSTRACT

This study was designed to investigate the quality changes in chicken nuggets fried in different mixtures of hydrogenated and non-hydrogenated canola oils. Food colour, texture (maximum load to puncture), oil and moisture content were investigated. Proportions of hydrogenated to non-hydrogenated oils used in the study were 0, 20, 40, 60, 80 and 100%. The products were fried at 190°C for 30, 60, 90, 120, 180, 240 and 300 seconds. Increasing frying time decreased product lightness (L^*) whereas redness (a^*) and yellowness (b^*) increased. The maximum load values also increased with increasing frying time. The oil content of fried product also slowly increased with frying time and moisture content decreased as expected. However, both oil and moisture contents tended to equilibrium values after 240-300 seconds frying. Both frying time and oil types had significant effects on all of the quality parameters, namely colour, texture, oil and moisture contents. The first order kinetic equation was used to represent the development of colour, oil and moisture content. The result showed that oil and moisture content followed a negative regression relationship. With increasing degree of hydrogenation, the surface colour of fried chicken nuggets tended to be lighter, the maximum loads increased, and oil and moisture contents tended to decrease.

3.2 INTRODUCTION

Deep-fat frying (DFF) is one of the oldest methods of food preparation (Varela and Ruiz-Ruso, 1998) and fried foods are accepted by consumers all over the world. In North America, fried chicken is an important food served at almost all fast foods restaurant chains. Surface appearance and texture are the most significant factors for consumer acceptability. Oil content also had become another important parameter for evaluating product quality due to consumer's preference for reduced fat in fried products.

Most foods cook rapidly at the frying temperature of 160 to 190°C and they develop a golden colour, crisp texture and good flavor (Dunford, 2004). The linkage between colour and consumer perceptions of quality is often psychological. Instrumental measurement of texture and colour can offer a quantified basis for manipulating processing variables for quality improvement. Paul and Mittal (1996) examined how the degradation of canola oil during frying affected the colour of the fried chicken. The authors observed a high correlation between colour parameters and oil degradation during frying. Ateba and Mittal (1994) modeled kinetics of development of crust colour in meatballs during frying using first-order reaction kinetics. Krokida et al. (2001b) also applied the first order kinetic model to describe colour changes in French fries during the frying process. Oil temperature and sample thickness were the process parameters significantly affecting the colour during frying. Therefore colour changes became more intense at higher temperatures and smaller sample thickness (Krokida et al., 2001b). Apart from cross-sectional thickness of a sample and frying oil temperature, concentration of hydrogenated oil affect colour changes during deep-fat frying as reflected by the reaction rate constant (k) (Krokida et al., 2001b; Baik and Mittal, 2002).

Another important quality attribute of fried products is crispness. The forming of a crispy crust depends on both the product and process conditions. Force-deformation studies have been performed by several researchers to predict texture of fried products, such as French fries and tortilla chips (Fan et al., 1997). In general, a fried product becomes tougher as the frying time increases up to an optimum value after which the product becomes brittle. Mass transfer during frying consists of moisture loss and oil absorption. Moisture loss during frying generally decrease exponentially with frying time. Costa and Oliveira (1999) suggested that predicting water loss is critical for modeling and controlling the deep-fat frying of potatoes. Studies on tortilla chips suggest that most of the oil does not penetrate the product during frying, but does so during the cooling period when the product is removed from the fryer (Gamble et al., 1987; Moreira et al., 1997). There are indications that this might not be case for other products. The dynamics of moisture outflow, as well as oil uptake, has been described using first-order mass transfer kinetics (Krokida et al., 2001b). Several authors correlated fat absorption and moisture loss; a linear relationship was reported throughout deep-fat frying between oil uptake and moisture loss (Kassama and Ngadi, 2001; Gamble et al., 1987). Moisture loss was often assumed to be controlled by internal diffusion based on mass transfer theories. Fat absorption is dependent on the initial moisture content of the food product being fried. Foods are hygroscopic materials and carry significant quantities of bound water in their porous matrix. As a result, as water diffuses from the matrix during frying, pathways usually referred to as capillary pores are formed and subsequently filled by oil. Some authors (Kassama and Ngadi, 2004; Gamble et al., 1987) suggested that high frying temperatures cause formation of crust which facilitates oil absorption. Thus, mass transfer process and development of texture characteristics during frying are related.

Frying oil, as a mass and heat transfer medium, not only affects food product quality and production cost but also relates to health factor which is a critical evaluation to fried product. The quality of the frying oils and the fried food product is intimately related (Blumenthal, 1991). Hydrogenated oils are widely used in food industry due to their stable chemical structure and longer shelf life. However, hydrogenated oil contains trans-fatty acids that are not of benefit to consumers' health. Non-hydrogenated oils contain less trans-fatty acids, but the unstable molecular structures make them easy to degrade and the products have short shelf life. Due to their different oxidized stabilities, hydrogenated and non-hydrogenated oil have different performance on the quality of foods fried in it, hence this study.

3.3 OBJECTIVES

The objectives of this study were to investigate changes in quality characteristics namely surface colour and texture of chicken nuggets during deep-fat frying; and to evaluate the relationships between the quality attributes with oil and moisture transfer during the frying process.

3.4 MATERIALS AND METHODS

3.4.1 Chicken nuggets samples

Commercial, ready-to-fry and frozen chicken nuggets were purchased from a major local manufacturer. The average weight of the slab shaped chicken nugget was 21g. The size of the commercial samples was about 5 cm (length) x 3 cm (width) x 1 cm (thickness) (± 0.5 cm). The chicken nugget samples were stored in a freezer at -18°C till required for use. Before frying, frozen samples were removed from a freezer and thawed in a refrigerator at 4°C for 24 h.

3.4.2 Oil Samples

Hydrogenated canola oil was purchased from a local supplier (Canbra Foods Ltd., Lethbridge, AB), whereas non-hydrogenated canola oil was purchased from another local supplier (Sunfresh Ltd., Toronto, ON). Oil samples used for experiments were mixtures of hydrogenated and non-hydrogenated oils. Six different mixtures were formulated at the w/w ratio (hydrogenated oil to non-hydrogenated oil) of 100:0, 80:20, 60:40, 40:60, 20:80 and 0:100.

3.4.3 Frying

Chicken nuggets were fried in 3 kg oil blend (mixture of hydrogenated and non-hydrogenated oil) in a domestic electric fryer (5 L). The frying oil was maintained at ±2°C of the set temperature (190°C) using a programmable temperature controller (Eutech Instrument Pte Ltd., Singapore). The fresh oil was preheated at 190°C for 2 hours prior to normal frying. Three samples were fried in each frying batch to reduce temperature fluctuations during frying. The samples were placed in a wire basket to keep them submerged for the required times of 30, 60, 90, 120, 180, 240 and 300 seconds. The temperature of the frying oil was monitored using a T-type thermocouple (copper vs. constantan). After frying, samples were immediately withdrawn from oil, and blotted gently with dry tissue paper to remove excess oil on the surface. The samples were allowed to cool to room temperature before further tests. Oil and moisture content of the samples were measured, as well as their texture and colour attributes.

3.4.4 Experimental design

All experiments were performed in three replicates in order to ensure better analysis of the statistical data. The data were subjected to the analysis of variance (ANOVA) and Duncan's multiple range tests. Significance was based on 5% level in all cases.

3.4.5 Colour determination

Colour measurements were by using the colorimeter (Minolta CR 300, Minolta Camera Co. Ltd., Osaka, Japan). The samples were placed in a transparent Petri dish and positioned directly on the light path to measure to relevant colour parameters values (L*, a* and b*). Two colour readings were taken from each chicken nugget sample and the average was used for analysis. Chroma (C^*) was calculated using the following equation (Minolta, 1992):

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{3.1}$$

3.4.6 Moisture content

Moisture content was determined using the AOAC standard method (39.1.02). The fried samples were weighted in an electric scale (TR-4102D, Denver Instrument Co., Denver, CO), and then dried in a conventional oven (Isotemp 700, Fisher Scientific, Pittsburgh, PA) at 102°C for 18 hours. The samples were placed in a desiccator to cool down and weighed. The moisture was determined by difference in weight in terms of dry basis.

3.4.7 Fat extraction

Fat content was determined using Soxhlet extraction technique according to AOCS standard method Aa 4-38 (1993). The dried fried chicken nuggets samples were ground in a blender (Proctor-Silex, model E160B, Picton, ON). The ground sample (2-4 g) was weighed with an electronic scale (TR-4102D, Denver Instrument Co., Denver, CO) and placed in a thimble. Fat was extracted in a solvent extractor (SER148, Velp Scientifica, Usmate, Italy) using petroleum ether. The mass of the glass extraction cups with a few boiling stones was recorded and 50 ml petroleum ether was added to each cup.

The thimbles were then inserted to the magnetic connector of the extraction unit. The thimbles were immersed in the boiling solvent for 30 min and then submitted to 60 min of reflux washing and 30 min of drying to recover the solvent. The extracts were further dried at 102°C for 30 min to remove residue solvent and moisture. Then the sample cups were cooled in a desiccator and subsequently weighed. The oil content (OC) was obtained in terms of dry basis.

3.4.8 Textural analysis

The Instron Model testing machine (Instron Corporation, Canton, MA) equipped with a 500 N load cell was used in the hardness test. Hardness of a material can be related to its chewiness (chewability). Fried chicken nuggets hardness was tested by penetrating it with a 9-pin probe. The probe was allowed to penetrate a specified penetration depth of the chicken nuggets at a cross-head speed of 300 mm/min. The data obtained were in the form of maximum load that were recorded at a rate of 5 readings per second. Although a 9-pin probe was used, only 6 pins penetrated the sample due to the size of the chicken nuggets. All samples were tested within 10 minutes after frying. The samples were punched twice, once for each side of the sample. The parameters for hardness test were programmed and stored for later analysis using the Instron Series IX Automated Materials Testing System software package .

3.4.9 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. Analysis of variance was performed and statistical significance was determined at the 5% significant level. Duncan's Multiple Range mean separation was performed where the ANOVA procedure showed significance.

3.5 RESULTS AND DISCUSSION

3.5.1 Colour changes in fried chicken nuggets

The initial lightness (L^*) value of fried chicken nuggets was 78.86. This decreased with frying time as shown in Figure 3.1. The change was apparently rapid at the early stage of frying, but it became slower at longer frying times. After 300 seconds of frying, the lightness values ranged from about 52 to 59 depending on the different oil types. The Analysis of variance (ANOVA) (Appendix I-A) revealed that the degree of hydrogenation and frying time had significant effect ($P<0.05$) on lightness of fried chicken nuggets. Separation of means analysis showed that the effect of oils on lightness of chicken nuggets could be divided into two groups. Frying in oils, with lower degrees of hydrogenation (0 and 20%), resulted in products with significantly lower lightness values ($P<0.05$) compared to frying in oils with higher degrees of hydrogenation (40-100%). The lightness data can be adequately described by the first order reaction kinetics.

As with lower degrees of hydrogenation (0 - 20%), the model ($R^2 = 0.95$) was

$$L^* = 76.82\, e^{-0.046\, t} \tag{3.1}$$

As with higher degrees of hydrogenation (40 -100%), the model ($R^2 = 0.98$) was

$$L^* = 79.24\, e^{-0.041\, t} \tag{3.2}$$

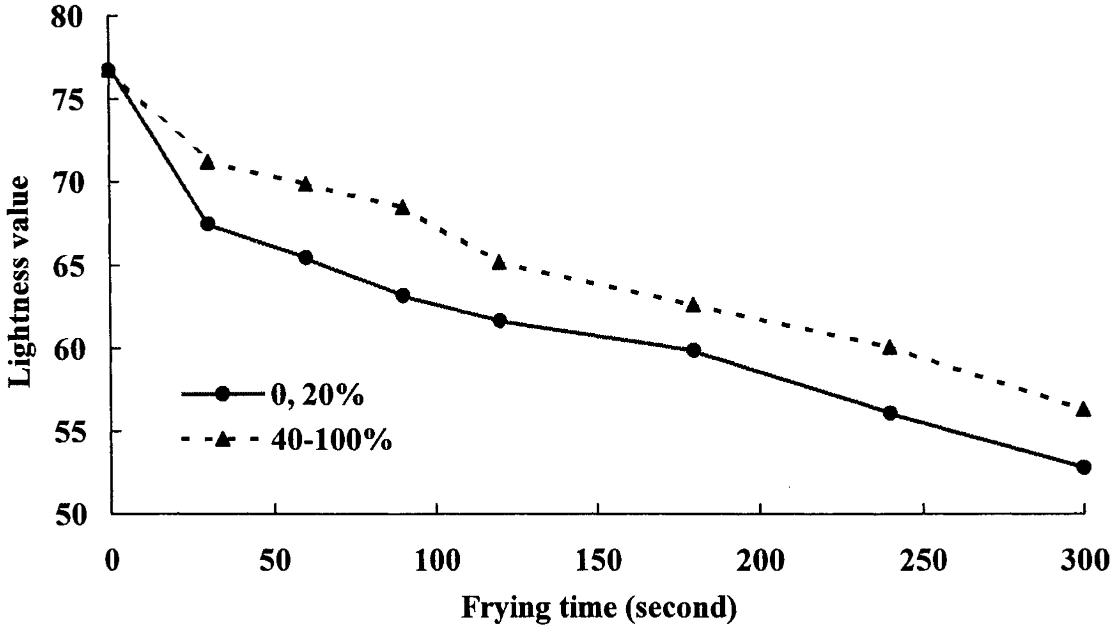

Figure 3.1 Average lightness values (L*) obtained for chicken nuggets fried in oils with different degrees of hydrogenation. The percentage refers to the w/w ratio of hydrogenated oil.

Other authors (Baik and Mittal, 2003; Ozdemir and Devres, 2000; Krokida et al., 2001b; Sosa-Morales and Vélez-Ruiz, 2002) have modeled colour changes of different foods during frying using first-order reaction kinetics. Baik and Mittal (2003) reported that lightness (L^*) of tofu decreased exponentially during 5 min frying in hydrogenated oil. Sosa-Morales and Vélez-Ruiz (2002) reported similar results with fried pork strips. Krokida et al. (2001a) also obtained similar results for potato strips. This study established the similar phenomenon as reported by the various authors. Ramirez et al. (2004) fried pork loin chops in olive oil, sunflower oil, butter and pig lard and observed a significant difference in lightness due to the different types of frying fat used. However, Krokida et al. (2001a) reported a negligible effect of oil types on lightness of French fries. Therefore, the influence of oil on colour may vary for different products. The results obtained in this study for chicken nuggets maybe due to the complex chemical components of breaded and batter coated chicken nuggets. The decrease in L^* with time may be attributed to Maillard browning and caramelization at high frying temperatures. The rate of the Maillard reaction depends on its chemical environment, such as water activity, pH, chemical composition of the food and the reaction temperature (Carabasa and Ibarz, 2000). From the point of view of producing lighter coloured fried chicken nuggets, our results showed that a shorter frying time and oils with low degree of hydrogenation are preferred.

The average redness (a^*) value of the chicken nuggets increased from initial –0.25 to 14.5 (after frying 300 seconds) depending on oil types. The a* values also increased significantly ($P<0.05$) with frying time and the degree of oil hydrogenation (Appendix I-B). Separation of means analysis showed that the effect of oils on redness of chicken nuggets could also be divided into two groups. Frying in oils with lower degrees of hydrogenation (0, 20 and 60%) resulted in products with significantly ($P<0.05$) lower redness values compared to frying in oils with higher degrees of hydrogenation (40, 80 and100%). Redness may not be a desirable colour in fried food products in general (Krokida et al., 2001b). Ramirez et al. (2004) reported that the frying fat types had a significant effect on redness of fried pork loin chops. Baik and Mittal (2003), Krokida et al. (2001a) reported that a^* values of potato strips increased exponentially depending on frying conditions.

The yellowness (b^*) of chicken nuggets increased quickly from the initial value of 18.5 during first 60s frying. Then b^* value tended to equilibrate at the maximum value of about 38.8 to 46.5 after frying for 240s. Similar results were also observed in the research on tofu (Baik and Mittal, 2003). ANOVA (Appendix I-C) showed that both the degrees of hydrogenation and frying time had a significant effect ($P<0.05$) on the yellowness of fried chicken nuggets. Similar to the results obtained for L^* and a^*, the separation of means analysis showed that the effect of oils on yellowness of chicken nuggets could be divided into two groups. Frying in oils with lower degrees of hydrogenation (0 and 20%) resulted in products with significantly lower yellowness values compared to frying in oils with higher degrees of hydrogenation (40-100%).

The chroma (C^*) index was used to describe the colour saturation of chicken nuggets, which combines redness and yellowness and could effectively indicate the colour changes of fried chicken nuggets. Chroma increased rapidly in the earlier frying stage and then the changes tended to slow. After 300 seconds of frying, the value of C^* had increased from initial value of 18.5 to values in the range of 39.6 - 46 depending on oil types as shown in Figure 3.2. ANOVA (Appendix I-D) showed that both the degrees of hydrogenation and frying time had a significant effect ($P<0.05$) on chroma of fried chicken nuggets. Separation of means analysis explained that the effect of oils on chroma of chicken nuggets could be divided into two groups. Frying in oils with lower degrees of hydrogenation (0 and 20%) resulted in products with significantly lower C^* values compared to frying in oils with higher degrees of hydrogenation (40-100%).

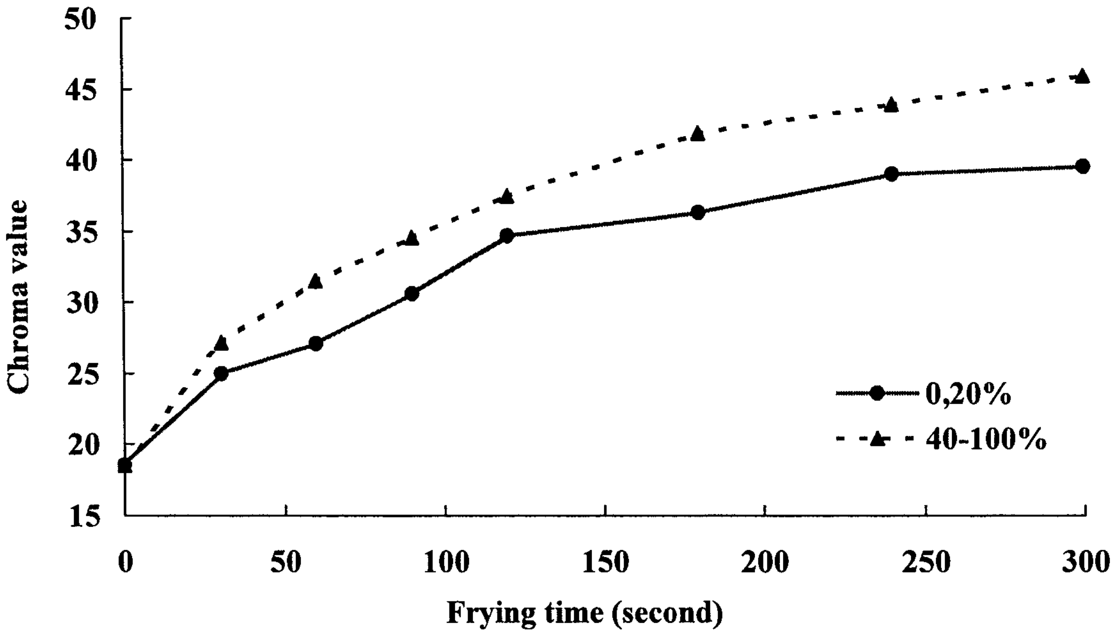

Figure 3.2 Average chroma values (C^*) obtained for chicken nuggets fried in oils with different degrees of hydrogenation. The percentage refers to the w/w ratio of hydrogenated oil.

The chroma data was adequately described by the first order reaction kinetics. As with lower degrees of hydrogenation (0 and 20%), the model ($R^2 = 0.91$) was

$$C^* = 19.30\ e^{0.102\ t} \tag{3.3}$$

As with higher degrees of hydrogenation (40-100%), the model ($R^2 = 0.88$) was

$$C^* = 20.15\ e^{0.116\ t} \tag{3.4}$$

Yellowness is the preferred fried food colour that is related to the golden surface colour of chicken nuggets developed during frying. The coating and breaded ingredients attributed to produce redness and yellowness of fried product in this study. Additionally, as a combined factor of a^* and b^* values, chroma reflects colour purity or saturation, so it could be a good indicator of consumer acceptance. The lower degree hydrogenated oil and the shorter frying time maybe used to produce fried nuggets with lower redness. Apart from the complex chemical reactions involved, the nature of heat transfer from the oil to the product may have contributed to colour development during frying. Since the hydrogenation process increases oxidative and thermal stability of oils, there may have been differences in the heating characters of non-hydrogenated and hydrogenated oil. These may have resulted in different heat transfer coefficient and varied the amount of heat transferred to the product

3.5.2 Texture analysis

A typical stress-strain graph of fried chicken nuggets is shown in Figure 3.3.

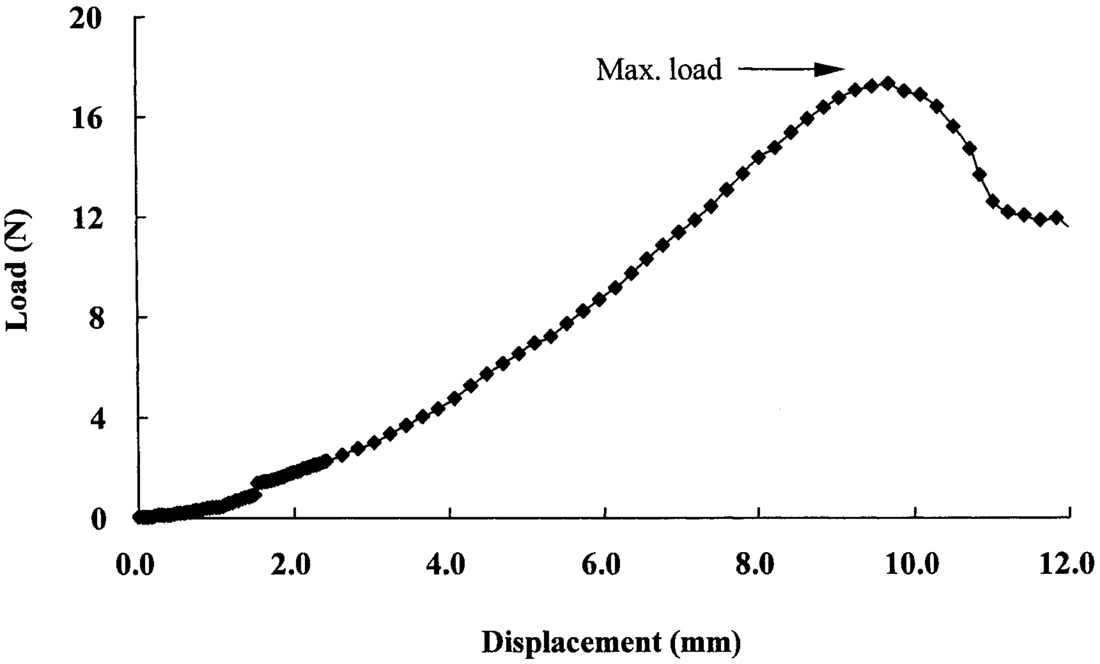

Figure 3.3 Typical stress-strain diagram obtained for fried chicken nuggets

The maximum load value for the thawed raw chicken nugget was about 1.0 N, which reflected the mushy and soft texture of thawed, uncooked chicken nuggets. Upon frying, the texture toughened, as shown in Figure 3.4. The maximum load values increased rapidly during the first 60s of frying. This could be associated with a greater moisture loss, starch gelatinization and protein denaturalization. Afterwards, changes in the values of the maximum load tended to decrease. ANOVA (Appendix I-E) showed that both frying time and oils had significant effect ($P<0.05$) on maximum load. Separation of means analysis showed that that the effect of oils on texture of chicken nuggets could be divided into three groups. Frying in oils with lower degrees of hydrogenation (0 - 60%) resulted in products with significantly lower maximum load values compared to frying in oils with higher degrees of hydrogenation (80 and 100%). Higher values of maximum load indicate an increase of crispy texture of nuggets.

The changes in the textural properties of fried chicken nuggets can be attributed to the physical and chemical changes taking place during the frying process, particularly in the batter/breading portions. Suderman (1983) and Loewe (1993) related textural changes with moisture loss, protein denaturation and starch gelatinization. In addition, the degree of oil hydrogenation was also a factor affecting food texture. Generally, fluids with higher viscosity and/or higher density have a higher convection heat transfer coefficient. The rate of heat transfer to the surface of the food product may have increased with increasing degree of hydrogenation of the oils and resulted in the increased maximum load and harder surface. Thus, a longer frying time and a higher degree of hydrogenated oil benefit for getting a crisper fried food.

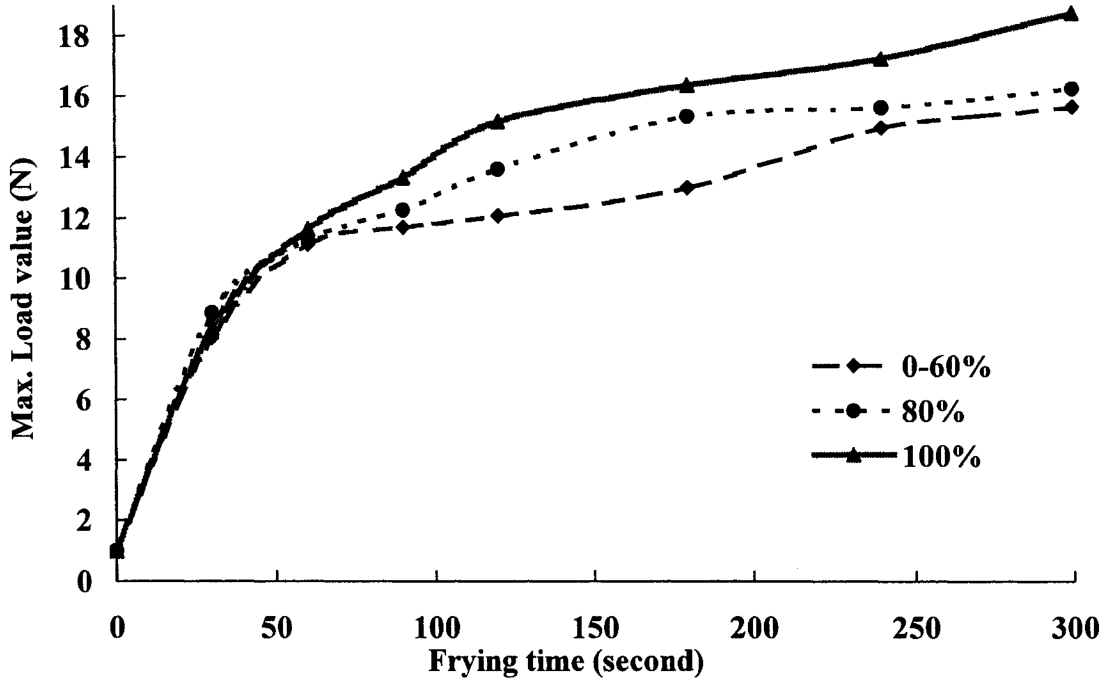

Figure 3.4 Average maximum load values of chicken nuggets fried in oils with different degrees of hydrogenation. The percentage refers to the w/w ratio of hydrogenated oil.

3.5.3 Oil content

The oil content of chicken nuggets ranged from initial 14 to 23.3% after frying for 300 seconds (Figure 3.5). Oil content increased faster at the earlier stage of frying which is associated with faster moisture loss. Chicken nuggets fried in non-hydrogenated oil contained higher oil content (23.3%) compared with samples fried in hydrogenated oil (21.6%).

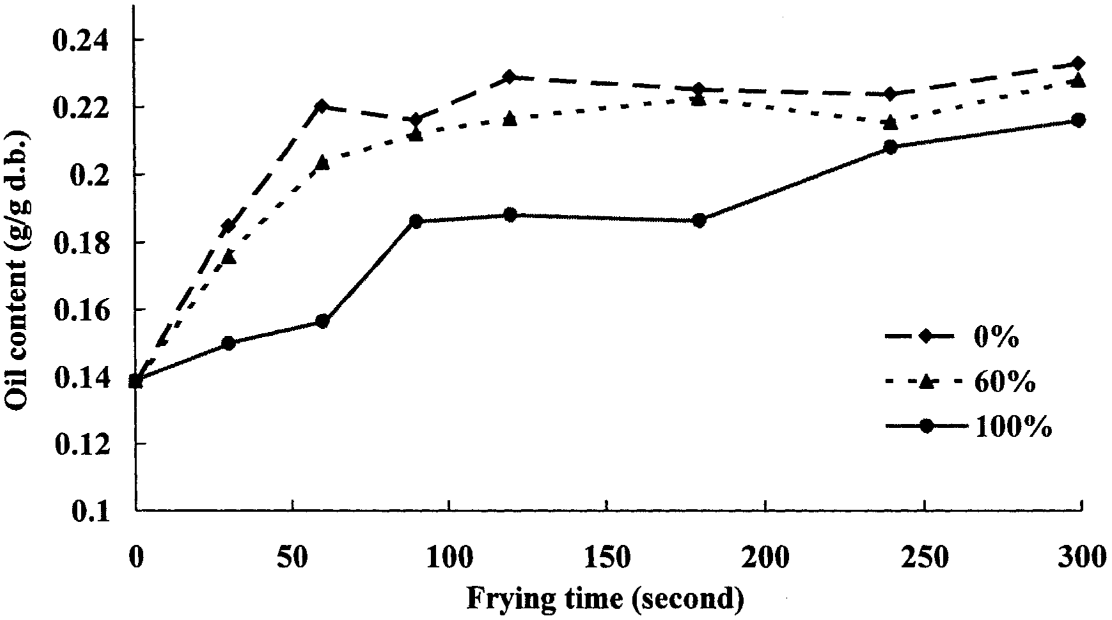

Figure 3.5 Average oil content values obtained for chicken nuggets fried in oils with different degrees of hydrogenation. The percentage refers to the w/w ratio of hydrogenated oil.

The ANOVA (Appendix I-F) revealed that both frying time and oil types had significant effect ($P<0.05$) on the final oil content of fried chicken nuggets ($P<0.05$). As shown in Figure 3.5, the oil content increased with increasing frying time. The higher the degree of hydrogenation, the lower the oil content. The equations for oil uptake can be written using first-order mass transfer kinetics (Krokida et al., 2001b). The data of oil content can be described as shown in Table 3.1.

Table 3.1 Estimated oil content development kinetic model

Hydrogenated oil (%)	a	b	R^2
0	0.162	0.087	0.8
20	0.149	0.067	0.83
40	0.135	0.084	0.94
60	0.150	0.069	0.83
80	0.133	0.072	0.95
100	0.133	0.066	0.93

The main process parameters influencing oil uptake are frying temperature and duration (Cuesta et al., 2001). Moreira et al. (1995) assumed that oil accumulated on the surface and entered during cool down. However, Diaz et al. (1999) and 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. The moisture lost during frying is normally replaced by an uptake of fat. This study showed that the degree of oil hydrogenation also contributed to oil uptake. Oil stability increased with increasing degree of hydrogenation. As the oil degrades, more surfactants are formed, causing increased contact between food and oil. This apparently resulted in an increased rate of heat transfer to the surface of the food. Eventually, excessive drying of the surface occurs, which causes increased oil absorption and a higher rate of heat transfer to the surface of the food. Non-hydrogenated oil is unstable during long-term frying/heating and they are more susceptible to degradation. The experimental data showed that chicken nuggets fried in oils with a lower degree of hydrogenation contained more oil than that fried in oils with a higher degree of hydrogenation.

3.5.4 Moisture content

The loss of moisture during frying is shown in Figure 3.6. The initial moisture content of chicken nuggets was about 2.1g/g db. In the first 30 seconds of frying, the moisture content decreased rapidly by 0.5-0.6 g/g db during which the raw chicken nugget absorbed heat from the surrounding media and was heated from its initial temperature to a temperature where the moisture began to evaporate from the nugget After this period, the rate of moisture content change showed a stable, but decreasing trend, as heat was transferred from the oil to the nugget The final moisture content of fried chicken nuggets after 300 seconds ranged from 1 to 1.2 g/g db depending on oil types.

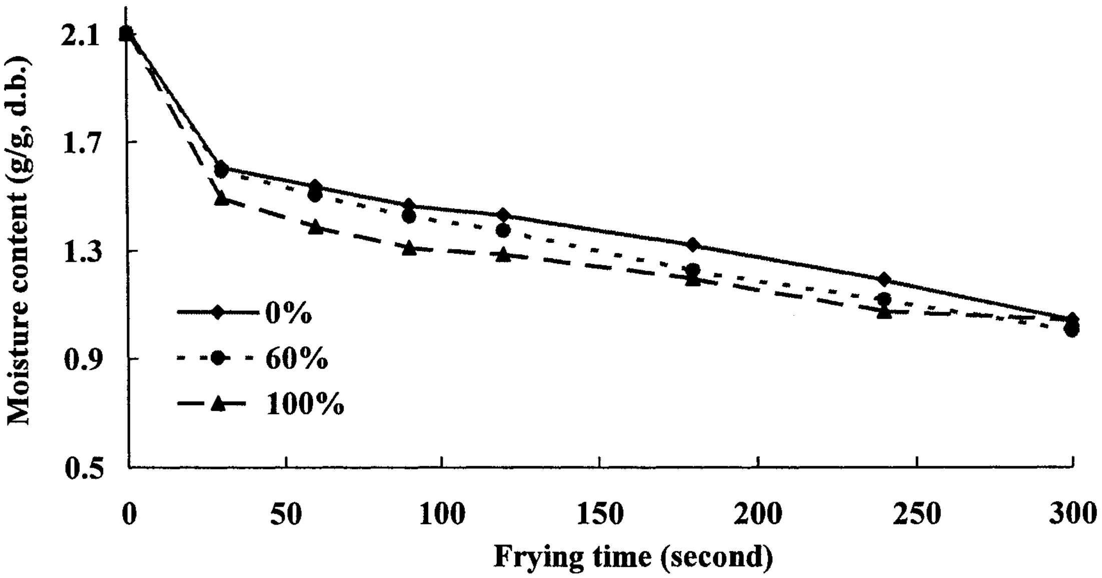

Figure 3.6 Average moisture content values obtained for chicken nuggets in oils with different degrees of hydrogenation. The percentage refers to the w/w ratio of hydrogenated oil.

Moisture content decreased significantly ($P<0.05$) with increasing of time during frying (Appendix I-G). The effect of oil types on moisture content was also significant ($P<0.05$). With increasing degree of hydrogenation, the moisture content of fried chicken nuggets tended to decrease. Many authors (Morgan et al., 1991; Ngadi and Correia, 1995; Ngadi, 1995) estimated moisture diffusivity models during the deep-fat frying process. Huang and Mittal (1995) developed heat and moisture transfer models for oven baking and boiling of beef meatballs. Moreira et al. (1995) used diffusion equations for moisture, heat and fat transfer during tortilla chip frying. In this study, we proposed that an empirical first order kinetic model could properly present the moisture loss during deep-fat frying of chicken nuggets as shown in Table 3.2.

Table 3.2 Estimated moisture content development kinetic model

Hydrogenated oil (%)	a	b	R^2
0	1.821	-0.117	0.9
20	1.814	-0.116	0.89
40	1.780	-0.125	0.87
60	1.804	-0.126	0.9
80	1.693	-0.122	0.82
100	1.932	-0.082	0.85

Several authors (Gamble et al., 1987; Ufheil and Escher, 1996; Krokida, 2000) correlated fat absorption and moisture loss; a linear relationship was reported throughout deep-fat frying between oil uptake and moisture loss. In this study, a negative linear relationship (–0.864) was established between moisture content and oil content. Frying time showed a good positive linear correlation (0.875) with moisture content, but a negative correlation (-0.869) with the oil content of fried chicken nuggets.

During deep-fat frying, moisture content is an important factor in determining oil uptake. 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. Foods with a high moisture content normally result in a high oil uptake during the frying process. Figure 3.7 describes the oil/moisture content changes during frying. With the increase of frying time, the ratio of the oil to moisture content increases, it indicates that the oil content keep increasing and the moisture content keep decreasing during the frying process. The ratio is also affected by the degree of oil hydrogenation. Fried in oils with lower degrees of hydrogenation, chicken nuggets have a high oil/moisture ratio. Due to the unstable chemical structure, non-hydrogenated oil is easier to degrade and causes excessive oil absorption and an increased rate of heat transfer to the food.

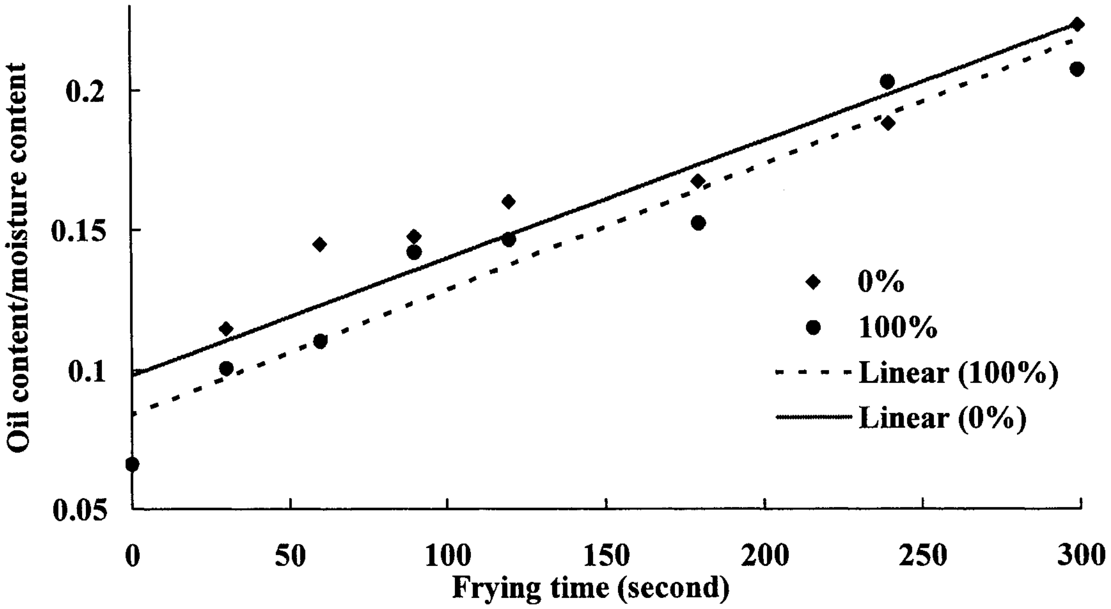

Figure 3.7 Oil content/ moisture content change

Figure 3.8 shows the interaction between oil and moisture content of fried chicken nuggets. Higher oil content correlated well with a lower moisture content. Products fried in oils with a higher degree (80 - 100%) of hydrogenation normally have a lower oil content compared to samples fried in oils with lower degree (0 - 60%) of hydrogenation. The interactions can be described by linear regression models. Oils with lower degree (0 - 60%) of hydrogenation, the linear model ($R^2 = 0.92$) is

$$y = -0.092x + 0.335 \tag{3.5}$$

As with a higher degree (80-100%) of hydrogenation, the model ($R^2 = 0.91$) is

$$y = -0.136x + 0.357 \tag{3.6}$$

Where y is oil content and x is moisture content of product.

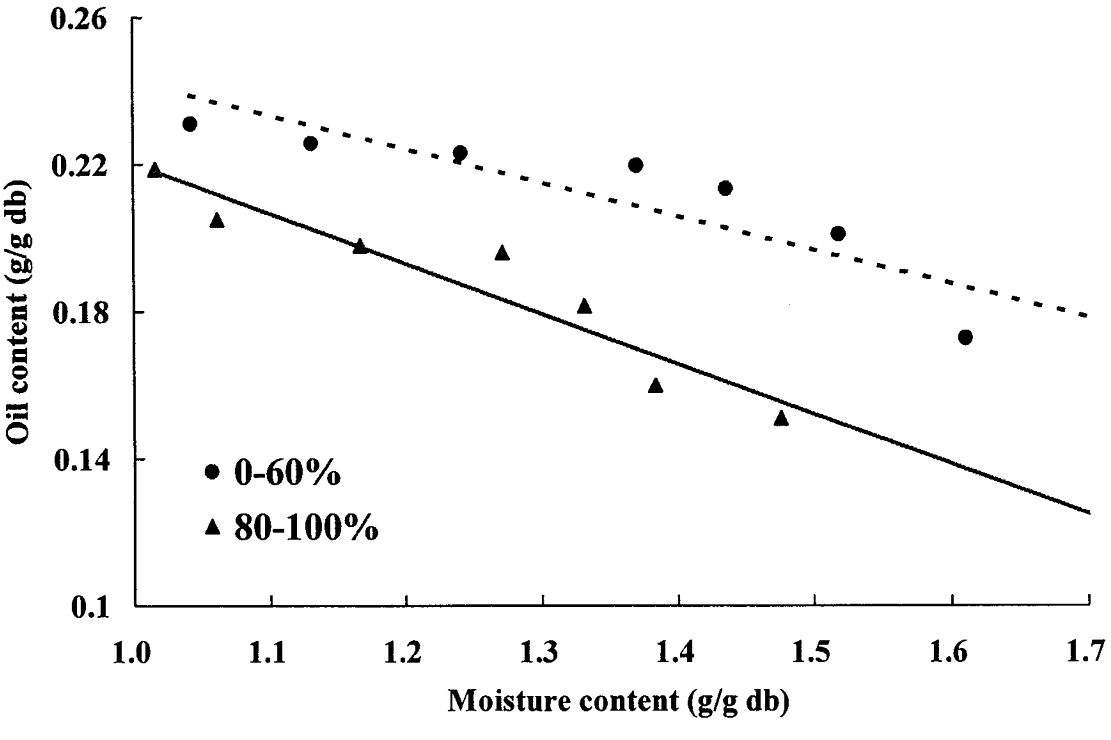

Figure 3.8 Interaction between oil and moisture content. The percentage refers to the w/w ratio of hydrogenated oil.

3.6 CONCLUSIONS

Based on data analysis, several conclusions can be drawn:

i. Oil types and frying time have a significant effect on the quality properties of fried chicken nuggets, namely surface colour, texture, oil and moisture content.

ii. Colour indices (L^* and C^*) can be described by empirical first-order kinetic models. Increasing of the frying time apparently decreased lightness while the redness, yellowness and chroma increased. Fried in oils with a higher degree of hydrogenation, chicken nuggets were apparently lighter, while lower-degree hydrogenated oils may produce deeper-coloured chicken nuggets.

iii. Increasing of the frying time caused an increase in the maximum load values. The maximum loads increased with increasing of the degree of hydrogenation.

iv. The changes of oil and moisture content of fried chicken nuggets fitted first-order kinetic models. Oil and moisture contents show a negative correlation and they significantly decreased with increasing degree of hydrogenation.

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CONNECTING TEXT

As a heat transfer and mass transfer medium, frying oils play an important role in deep-fat frying. They not only provide nutrition, but also influence the fried food quality. Frying oils breakdown as a result of high frying temperature, thus physical and chemical changes occur in the oils. The resulting degradative materials will affect the quality of foods fried in it.

In the following chapter, the quality parameters of different frying oils were evaluated. The frying oils were blends of hydrogenated and non-hydrogenated oil mixed in different proportions. These quality parameters include oil colour, FFA (free fatty acid) content, viscosity and dielectric property. The main assumptions were that the hydrogenated and non-hydrogenated oil were pure and contains no impurity affecting quality of the fresh oils.

IV. QUALITY CHANGES IN FRYING OILS WITH DIFFERENT DEGREES OF HYDROGENATATION

4.1 ABSTRACT

The study was conducted to measure, compare and correlate oil quality parameters namely oil colour, viscosity, free fatty acid (FFA) content and dielectric properties, and investigate the change in properties of oils with different degree of hydrogenation during deep-fat frying of chicken nuggets. Proportions of hydrogenated to non-hydrogenated oils used in the study were 0, 20, 40, 60, 80 and 100%. Commercial chicken nuggets were fried at 190°C. The relationships among these parameters, frying time and oil types were investigated. First order kinetic equations were used to represent the changes in colour and oil viscosity. Linear models were used to describe the development of FFA content. Frying time and oil types had a significant effect on all of these properties. The results from this study would elucidate changes in oil colour, viscosity, FFA level and dielectric properties of frying oils with different degrees of hydrogenation.

4.2 INTRODUCTION

Frying oils, as the heat and mass transfer medium, have critical effect on the foods fried in it. They can affect the quality of foods in terms of *trans* fatty acid content, shelf life, nutrition and eating quality. The qualities of the frying oils and that of the fried foods are intimately related (Blumenthal, 1991). Oil quality may be influenced by the nature of the food fried, such as foreign oils, emulsifiers, trace metals, food scraps, free fatty acids, alkaline-reacting material or other components. Besides these, frying oils undergo physical and chemical reactions during heating that result in deterioration of their quality. During frying, a complex series of various chemical reactions takes place, such as thermoxidation, hydrolysis, polymerization and fission (Fritsch, 1981). The rate of decomposition depends on the composition of the oil, the temperature and length of frying, whether continuous or intermittent frying is used, the type of food fried, and whether or not fresh oil is added to replenish the frying oil (Paul and Mittal, 1996). Among these factors, the degree of unsaturation of the oil is the most important factor influencing the frying stability of the oil. When oils begin to degrade, heat capacity decreases and thermal conductivity increases thus resulting in higher energy consumption. Viscosity increases as a result of polymer formation, and the oil colour darkens (Blumenthal, 1991). Deterioration of frying oils is generally followed by changes in free fatty acid level, colour of the used oil, or an increase in the polarity of the oil (Melthon et al., 1994; Orthoefer, 1988; Orthoefer et al., 1996; Paradis and Nawar, 1981; Tan et al., 1985). Repeated use of frying oils produces undesirable constituents that may pose health hazards (Tyagi and Vasishtha, 1996). Therefore, various criteria have been developed to judge the best time to discard used oils.

Sensory evaluation is still the most widely used method to evaluate oil quality (Melton et al., 1994). Lovibond Colour (AOCS Cc 13E-92) may be used when developing quality standards for fresh oils. Lightness is normally not an important colour parameter to evaluate oils, because the lightness of oils sometimes depends on their sources. A red colour may correlates with the oxidized fatty acids and pyrolytic condensation products in the oil. A yellow colour may relate to the combined peroxides and aldehydes in an oil.

Free fatty acid (FFA) was normally measured to determine the relative stabilities of each oil towards oxidation and thermal deterioration under deep frying conditions. In the presence of moisture and heat, triglycerides decomposes into FFA during deep-fat frying. Elevated levels of FFA cause oils to smoke during frying, hasten oxidative degradation, and contribute to off-flavors (O'Brien, 1993). Fritsch (1981) reported no direct relationship between FFA content and the quality of used frying oil due to its volatilizable and unstable property. Although FFA is not a good parameter for comparing different frying processes or oil stability, it could be used as an indicator to evaluate oil quality (Saguy et al., 1996). So, the FFA content is also used in international regulation.

During frying, volatile and non-volatile decomposition products are formed within the medium. The formation of degraded products result in an increase in viscosity. This can be related to polymer development and a tendency toward foaming (Lawson, 1995; Tseng et al., 1996). In addition, as oxidation proceeds, oil viscosity also increases (Tyagi and Vasishtha, 1996).

The utility of the dielectric property has been increasingly recognized as a non-destructible, easy, quick, real time, and continuous method for evaluating changes in foods and biological materials (Fritsch et al., 1979). As oil undergoes thermal and oxidative breakdown, its dielectric constant increases. The dielectric constant continuously increase with increasing heating time. It has a good correlation with the acid value, density and relative viscosity. So dielectric property of oil can be used as a quick test of oil quality (Klepacki, 1965; Shi et al., 1998; Inoue et al., 2002).

Once frying oil begins to break down, the process is irreversible, and this eventually results in poor or unacceptable food (Blumenthal, 1988). It is important to understand the breakdown of hydrogenated and non-hydrogenated oils since this not only affects product quality but also affects production costs and consumer's health.

4.3 OBJECTIVES

The objectives of this study were to investigate changes in quality characteristics of different oil blends, namely oil colour, viscosity, dielectric properties and FFA content during deep-fat frying and to evaluate the relationships between oil properties, oil types and frying time.

4.4 MATERIALS AND METHODS

4.4.1 Chicken nuggets samples

Commercial, ready-to-fry and frozen chicken nuggets were purchased from a major local manufacturer (Olymel, Montreal, QC). The chicken nuggets were stored in a freezer at -18°C till required for use. Before frying, frozen samples were thawed in a refrigerator at 4°C for 24 h.

4.4.2 Oil Samples

Hydrogenated canola oil was purchased from a local supplier (Canbra Foods Ltd., Lethbridge, AB), whereas non-hydrogenated canola oil was purchased from another local supplier (Sunfresh Ltd., Toronto, ON). Oil samples used for experiments were mixtures of hydrogenated and non-hydrogenated oils. Six different mixtures were formulated at the w/w ratio (hydrogenated oil to non-hydrogenated oil) of 100:0, 80:20, 60:40, 40:60, 20:80 and 0:100.

4.4.3 Frying and sampling

Chicken nuggets samples were fried in 3 kg oil blend (mixture of hydrogenated and non-hydrogenated oil) in a domestic electric fryer (5 L). The frying oil was maintained at ±2°C of the set temperature (190°C) using a programmable temperature controller (Eutech Instrument Pte Ltd., Singapore). The fresh oil was preheated at the 190°C for 2 h prior to normal frying. The temperature of the frying oil was monitored using a T-type thermocouple (copper vs. constantan). Three chicken nugget samples were placed in a wire basket to keep them submerged. Nugget samples were fried for 5 min in each frying batch. Three batches were fried every 3 h. Oil samples were taken every 3 h for 18 h. The oil samples were allowed to cool to room temperature before further tests.

4.4.4 Experimental design

All experiments were performed in three replicates in order to ensure better analysis of the statistical data. The data were subjected to the analysis of variance

(ANOVA) and Duncan's multiple range tests. Significance was based on 5% level in all cases.

4.4.5 Colour determination

The equipment used for determining oil colour was a Minolta Spectrophotometer CM-3500d (Minolta Co., Ltd. Japan). Colour of frying oils was measured at the wavelength from 400 nm to 700 nm. 20 ml oil sample was transferred into a 5 cm-diameter petri dish and the thickness of oil was about 1 cm. The Petri dish was positioned directly on the light path to measure to relevant colour parameters values (L^*, a^*, b^* and transmittance). Three colour readings were taken from each oil sample and the average was used for analysis. Chroma (C^*) was calculated using the following equation (Minolta, 1992):

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \tag{4.1}$$

4.4.6 Viscosity measurement

All blended oil samples were rheologically characterized using a TA Instruments AR2000 stress-controlled rheometer (TA Instruments, US). The equipment was interfaced with a microcomputer for the data acquisition, the measured parameters were acquired through the microcomputer for further analysis. Three replicates were measured for each oil sample at 25 °C.

4.4.7 Free fatty acid determination

Composition of fatty acids was analyzed using AOCS procedure Ca 5a-40. The designated qualities (56.4 ± 0.2g) of sample was weighted into an oil-sample bottle or Erlenmeyer flask. Next the specified amount (50ml) of hot, neutralized alcohol (95%) and 2 ml phenolphthalein indicator was added into the flask. Finally the sample was titrated with 0.1N alkali, shaked vigorously until the appearance of the first permanent pink colour of the same intensity as that of the neutralized alcohol before addition of the sample. The colour must persist for 30 seconds. The percentage of free fatty acids in most types of fats and oils was calculated as oleic acid, the FFA content according to the formula below:

$$\text{Free fatty acids as oleic, \%} = \frac{\text{mL. of alkali} \times \text{N} \times 28.2}{\text{Weight of sample}} \tag{4.2}$$

4.4.8 Dielectric property

The dielectric property of all samples was measured by S-parameter Network analyzer (Agilent, 8722ES 50MHz-40GHz, US). The scanning scope was at 2450 kHz at room temperature. The equipment was interfaced to a microcomputer for data acquisition. All data were acquired through the microcomputer for further analysis.

4.4.9 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. Analysis of variance was performed and statistical significance was determined at the 5% significant level. Duncan's Multiple Range mean separation was performed where the ANOVA procedure showed significance.

4.5 RESULTS AND DISCUSSION

4.5.1 Oil colour

The redness (a^*) values of the oil samples are shown in Figure 4.1. The initial redness values ranged from –0.98 (non-hydrogenated oil) to –0.67 (hydrogenated oil). After frying/heating for 20 h, the final redness values ranged from –1.77 (non-hydrogenated oil) to –1.21 (hydrogenated oil). The decrease in redness values was relatively similar for all oil types, where the colour of all samples gradually darkened. The a^* values decreased significantly ($P<0.05$) with frying time (Appendix II-B). Oil types also significantly ($P<0.05$) affect redness. With increasing degree of hydrogenation, redness values increased gradually. The data fitted the first order kinetic models as shown in Table 4.1.

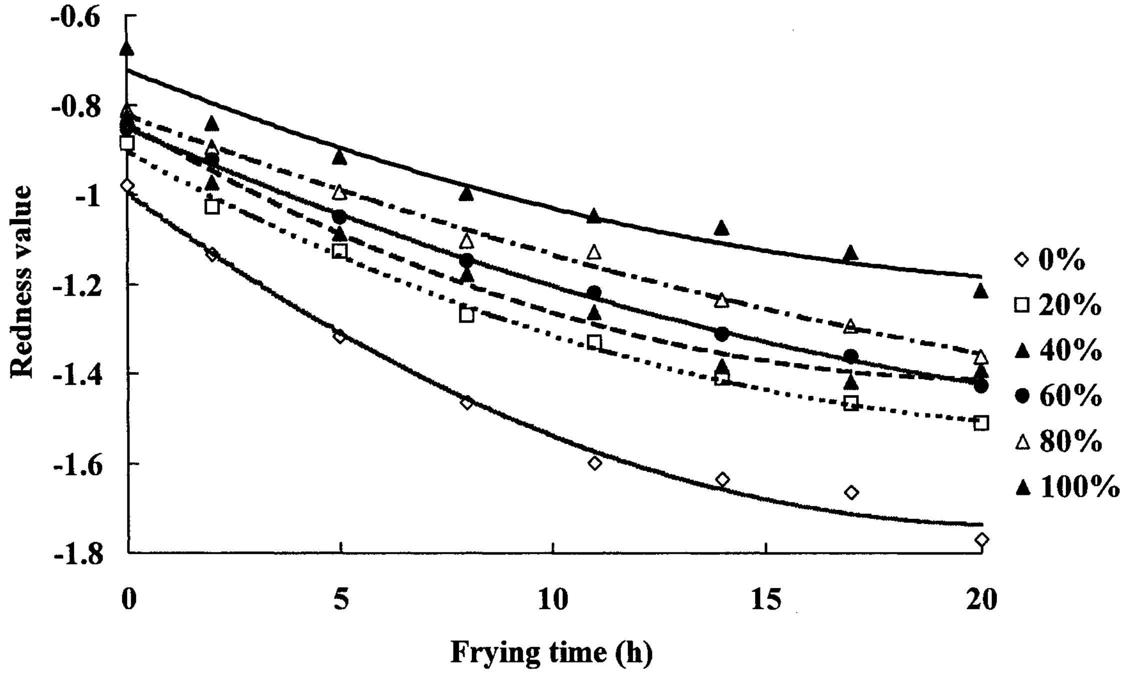

Figure 4.1 Average redness values (a^*) obtained for oil samples at different frying times

Table 4.1 Estimated redness (a*) development kinetic model

Hydrogenation Ratio (%)	a	b	R^2
0	9.055	-0.013	0.94
20	9.145	-0.001	0.92
40	9.213	-0.001	0.94
60	9.216	-0.001	0.96
80	9.236	-0.008	0.99
100	9.313	-0.007	0.94

The yellowness change of oils is shown in Figure 4.2. The initial yellowness values ranged from 1.85 (non-hydrogenated oil) to 0.75 (hydrogenated oil) depending on oil types. The final values of the yellowness value ranged from 6.22 (non-hydrogenated oil) to 3.28 (hydrogenated oil). Both frying time and oil types had a significant effect ($P<0.05$) (Appendix II-C) on yellowness. With increasing frying time, yellowness increased which was relatively similar for all oil types. As the degree of hydrogenation increased, the yellowness decreased gradually. The data fitted the first order kinetic model, where R^2 ranged from 0.92 to 0.99 (Table 4.2).

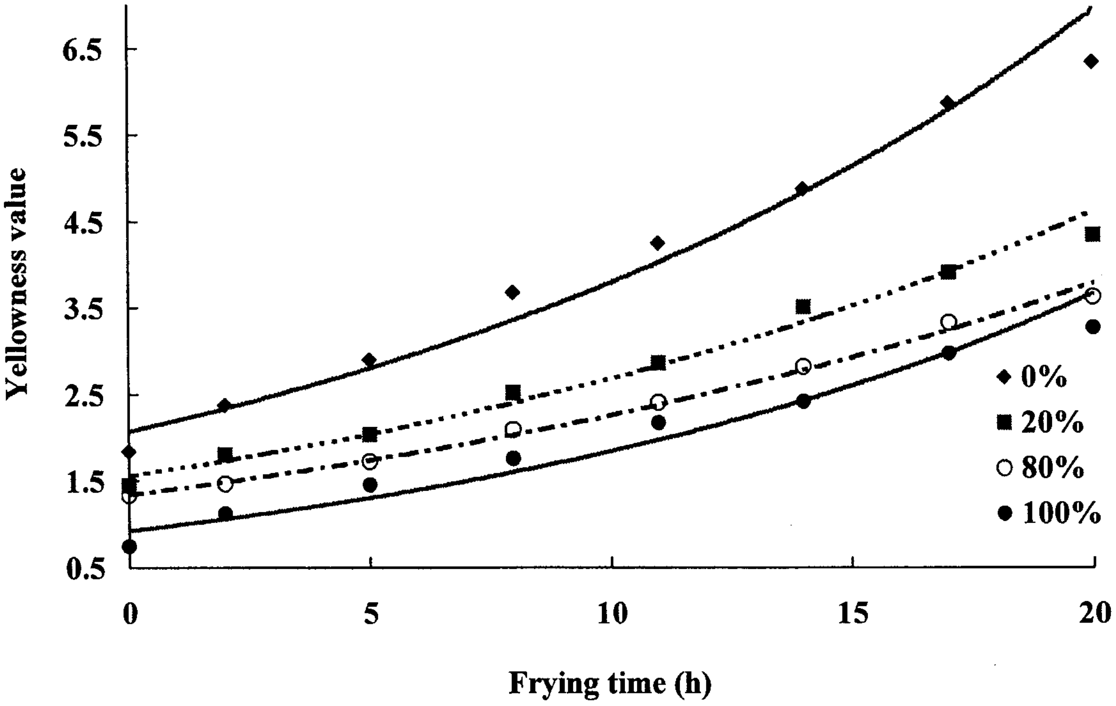

Figure 4.2 Average yellowness values (b^*) obtained for oil samples at different frying times

Table 4.2 Estimated yellowness (b^*) development kinetic model

Hydrogenation Ratio (%)	a	b	R^2
0	2.082	0.060	0.97
20	1.561	0.054	0.99
40	1.484	0.056	0.92
60	1.393	0.057	0.98
80	1.347	0.052	0.99
100	0.942	0.068	0.94

The chroma (C^*) index was used to describe colour saturation of oil samples, which combines redness and yellowness and could effectively indicate the colour change of oils. The initial C^* values ranged from 2.1 (non-hydrogenated oil) to 1.0 (hydrogenated oil). Upon frying, the chroma increased rapidly. After 20 h of frying/heating, C^* increased to 3.5-6.6 depending on oil types as shown in Figure 4.3. ANOVA report (Appendix II-D) revealed that frying time had a significant effect ($P<0.05$) on chroma of oil samples. Separation of means analysis showed that the effect of the degrees of oil hydrogenation significantly ($P<0.05$) affected oil chroma. As the degree of hydrogenation increased, the chroma values decreased gradually. The data fitted the first order kinetic models (Table 4.3), where R^2 ranged from 0.96 to 0.99.

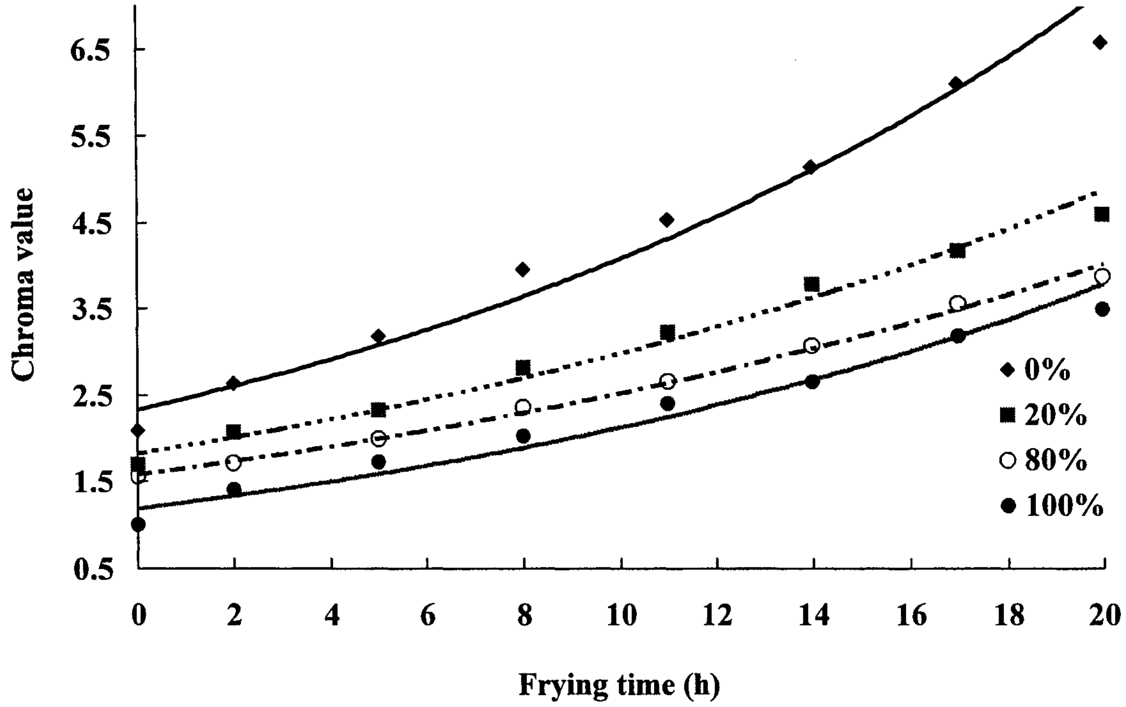

Figure 4.3 Average chroma values (C^*) obtained for oil samples at different frying times

Table 4.3 Estimated chroma (C^*) development kinetic model

Hydrogenation Ratio (%)	a	b	R^2
0	2.328	0.056	0.98
20	1.827	0.049	0.99
40	1.734	0.048	0.96
60	1.645	0.051	0.98
80	1.582	0.047	0.99
100	1.188	0.058	0.96

Oil colour was also evaluated by transmittance percentage. A standard full wavelength-scanning diagram is shown in Figure 4.4. Non-hydrogenated oil had the maximum value at about 570 nm, but hydrogenated oil and their mixtures had the maximum value at about 500 nm. In this research, the data at 500 nm were used for further analysis for all oil samples. Before frying, the transmittance percentage of oil samples ranged from 8.49 to 8.62. After frying/heating for 20 h, the transmittance percentage decreases to 7.95-8.24 depending on the different oil blends. A large number of degradation products are responsible for the colour development in degrading oils. Transmittance values increased significantly ($P<0.05$) with increasing frying time (Appendix II-E). Oil types also had a significant effect ($P<0.05$) on oil transmittance.

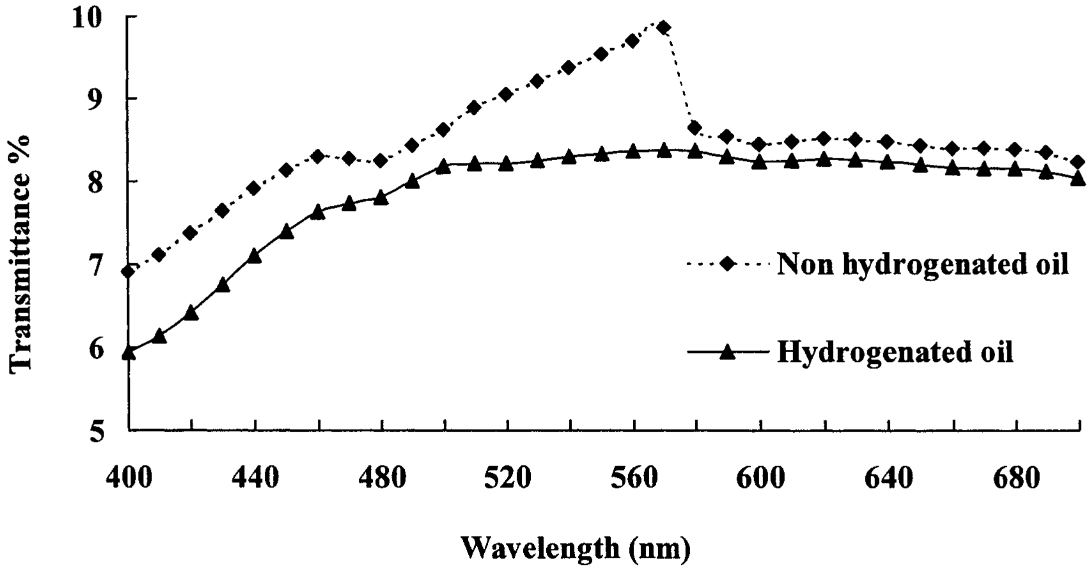

Figure 4.4 Full scope spectrometric scanning graph

Fresh oil has a light yellow colour. It changes rapidly to an orange brown colour on heating. The chroma (C^*) also showed significant ($P<0.05$) changes with increase in frying time. This change, in general, is a combined result of oxidation, polymerization and other chemical changes (Tan et al., 1985). Goburdhun et al. (2000) reported similar results in soybean oil research. Vijayan et al. (1996) also reported corn oil continued to darken with frying time. These conclusions were similar with the results obtained in this study. Darkening is attributed to the presence of unsaturated compounds or to non-polar compounds of foodstuff solubilized in the oil (Gutierrez et al., 1988). The darkeness of oil colour during frying is due to the fact that reactions between the aldehyde group of sugar and amino acids give brown products (Maillard reaction). In addition, the formation and accumulation of high molecular weight compounds may have also attributed to the increase in total colour (Mazza and Qi, 1992). Redness may be due to the formation of polymers, which promote the darkening of oil (Goburdhun and Jhurree, 1995). The yellow colour may be related to the combined peroxides and aldehydes in an oil. The colour change has also been attributed to the diffusion of food pigments into the oil during frying. Due to the stable chemical structure of hydrogenated oil, its colour change was not as severe as compared to non-hydrogenated oil.

4.5.2 Viscosity

The experimental viscosity data are depicted in Figure 4.5. Before frying, non-hydrogenated oil showed the lowest viscosity (0.06 Pa.S) while hydrogenated oil showed the highest value (0.083 Pa.S). The viscosities of all oil samples increased with increasing frying time. ANOVA (Appendix II-F) revealed that oil types and frying time had significant effect ($P<0.05$) on oil viscosity. With increase degree of hydrogenation, oil viscosities also increased. The data fitted the first order kinetic models as shown in Table 4.4.

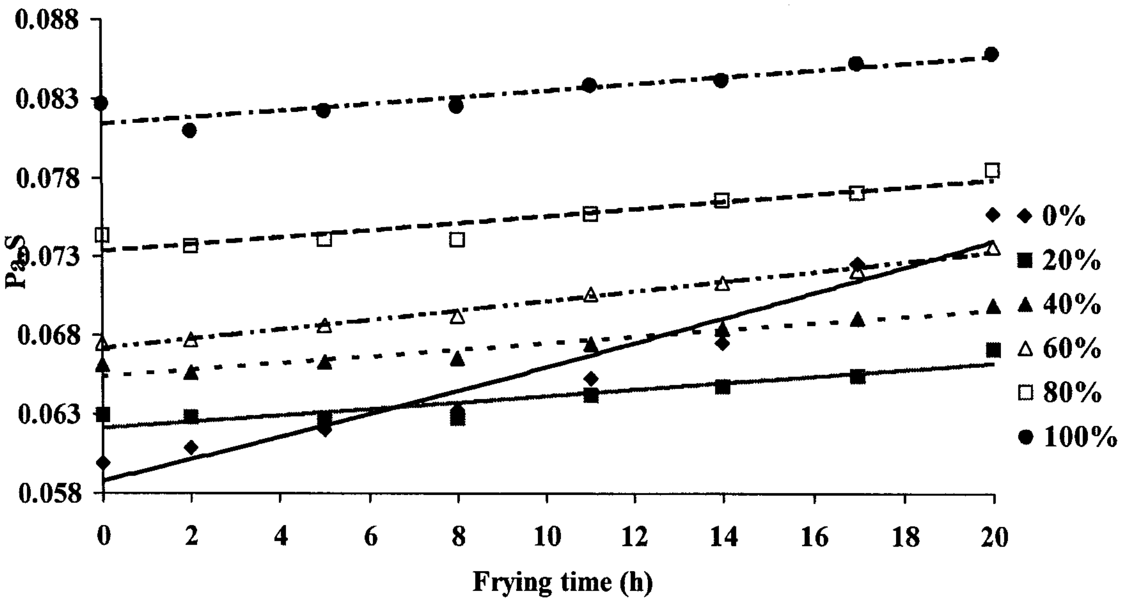

Figure 4.5 Average viscosity value obtained for oil samples at different frying times (at 25 °C)

Table 4.4 Estimated viscosity development kinetic model

Hydrogenation Ratio (%)	a	b	R^2
0	0.059	0.012	0.95
20	0.062	0.003	0.84
40	0.065	0.003	0.94
60	0.067	0.004	0.99
80	0.073	0.003	0.87
100	0.081	0.003	0.85

Many authors (Kassama and Ngadi, 2002; Tseng et al., 1996) reported that temperature has a significant effect ($P<0.05$) on oil viscosity. Kassama and Ngadi (2002) reported that all grades of oil exhibited a non-Newtonian or pseudoplastic behaviour within the temperature range of 10 to 40°C, while above 50°C, they behaved as a Bingham fluid. These results were similar to those obtained in this study. The increasing viscosity of frying oils has been related to oxidation and polymerization reactions (Gutierrez et al., 1988). Polymerization is said to result in the formation of higher molecular weight compounds (carbon-to-carbon and/or carbon-to-oxygen-to-carbon bridges) between fatty acids (Al-Harbi and Al-Kabtani, 1993) and lead to the formation of mainly dimeric and trimeric triglycerides, resulting in an increase in viscosity. The results of this study also clearly indicate the higher deteriorative effect of oxidation and polymerization on non-hydrogenated oil compared to hydrogenated oil, as reflected in the larger slope for non-hydrogenated oil.

4.5.3 Free fatty acid

The values of the FFA content of the samples during frying are shown in Figure 4.6. There was no apparent difference among the initial FFA contents of all oils. The FFA content increased with frying time for all oils. After frying/heating for 20 h, the FFA content of non-hydrogenated oil was significantly higher than the others as demonstrated by a steeper slope. Therefore, when oils are heated for the same time, non-hydrogenated oil more easily broken down.

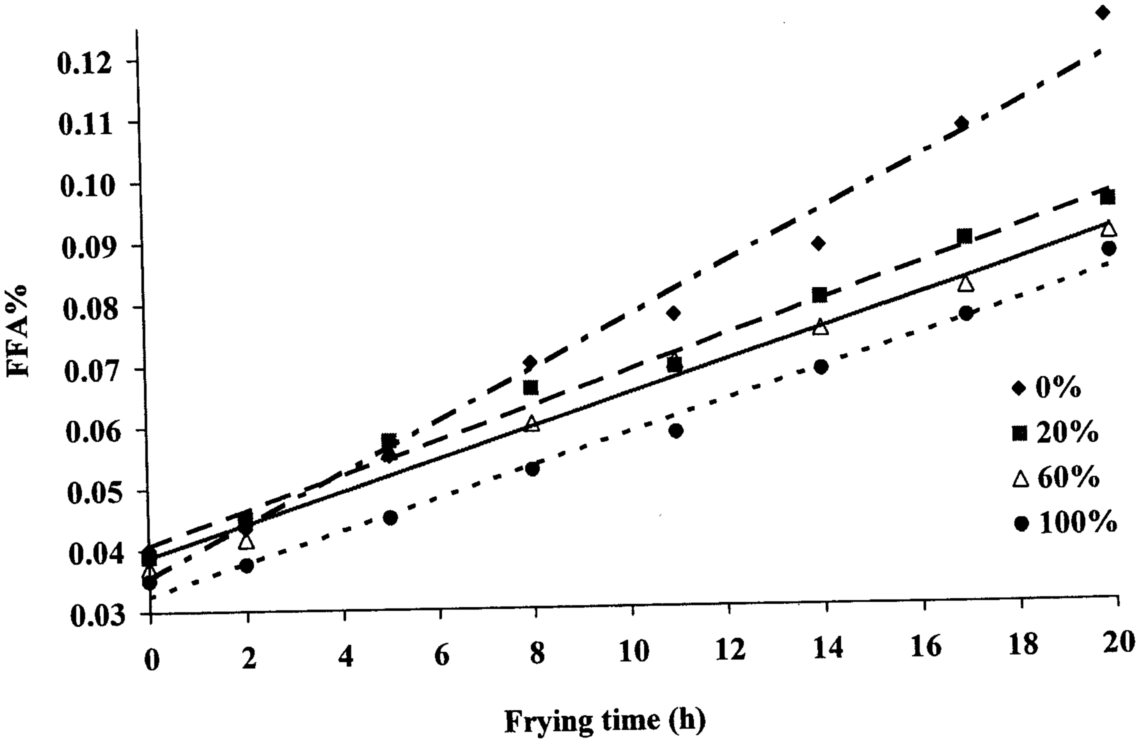

Figure 4.6 FFA content obtained for oil samples at different frying times

The ANOVA analysis (Appendix II-G) showed that both frying time and oil type had significant effect ($P<0.05$) on the FFA content. With increasing degree of hydrogenation, the FFA content of oil samples decreased. The relationship between FFA content and frying time can be described by linear equation as shown in Table 4.5.

Table 4.5 Estimated FFA content development kinetic model

Hydrogenation Ratio (%)	k	b	R^2
0	0.005	0.029	0.96
20	0.003	0.036	0.99
40	0.003	0.035	0.99
60	0.003	0.034	0.99
80	0.003	0.032	0.99
100	0.003	0.028	0.99

FFA determination is often used as a general indication of the conditions and edibility of oil (Kirk and Sawyer, 1991). The results of this study agreed with the findings of Naz et al. (2004) and Matalgyto and Al-Khalifa (1998) that the FFA content increased with frying time. The increase of fatty acid values during frying was due mainly to the hydrolysis and partly due to the carboxylic groups present in polymeric products of frying (Tyagi and Vasishtha, 1996). Hydrolysis is promoted by the presence of food moisture, and by oxidation or reaction of oil with moisture formed during other deterioration reactions (Al-Harbi and Al-Kabtani, 1993). The FFA level increased with frying time. Relatively lower levels of FFAs were observed in the higher degrees of hydrogenated oils. Hydrogenated oil is more stable, indicating better resistance to hydrolysis degradation.

4.5.4 Dielectric property

Figure 4.7 showed the dielectric constant of fresh oils and used oils at 2450 kHz. Fresh oils conduct very little electricity. The initial dielectric properties ranged from 2.41 to 2.56. However, after 20 h of frying/heating, the dielectric properties increased, ranging from 2.86 to 3.5 depending on oil types.

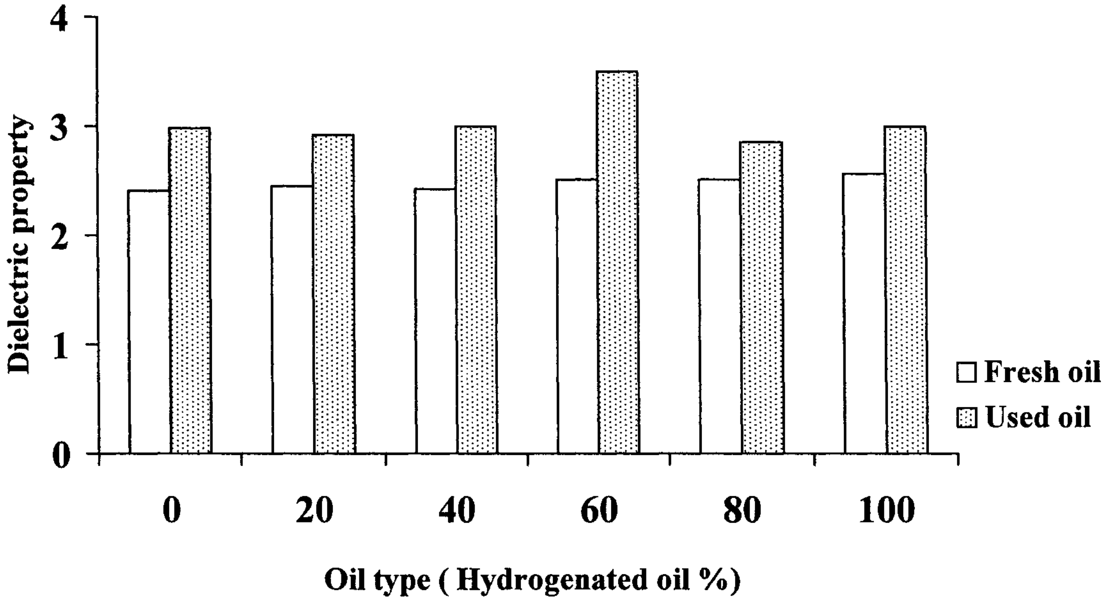

Figure 4.7 Dielectric property of fresh oil and 20 h used oil

The increase of the dielectric constant could be attributed to the formation of polar compounds resulting from the reaction between the frying medium, frying product and the environment. However, as oil is used, contaminants such as acids, moisture, and food scrap enter the oil. All of these contaminants elevate oil's ability to conduct electricity. The dielectric constant increased with increasing frying/heating time. By monitoring the increase, we can determine the level of contamination within the oil. Therefore, the dielectric property could be a good measure for the life of frying oil.

Table 4.6 showed the correlation between dielectric property and other parameters. Oil types had no apparent correlation with dielectric properties. There were no significant relationship between oil types and dielectric properties. Dielectric property has a good correlation with the frying time (0.876) and viscosity (0.785). In addition, good correlations can be found between other characteristics; for example, oil viscosity has a strong linear correlation with the frying time (0.93), and FFA content has a strong positive linear correlation with the concentration of hydrogenated oil (0.769).

Table 4.6 Correlation among dielectric property, viscosity, FFA, frying time and oil types

	Frying time	Oil type	Viscosity	FFA	Dielectric property
Frying time	1				
Oil type	0.000	1			
Viscosity	0.930**	-0.225	1		
FFA	0.415	0.769**	0.338	1	
Dielectric property	0.876**	0.115	0.785**	0.424	1

** Correlation is significant at the 0.01 level (2-tailed).

4.6 CONCLUSIONS

The conclusions are summarized as below:

1. Frying times and oil types had significant effect on oil colour, viscosity, FFA content and dielectric property.
2. All types of oils darken during frying, as reflected by redness (a^*), yellowness (b^*), chroma (C^*) and transmittance. With increasing frying time, a^* and transmittance percent decreased while b^* and C^* increased. With the increase of the degree of hydrogenated oil, a^* and b^* increased. All colour indices can be described with the first order kinetic models.
3. At 25°C, oil samples showed a non-Newtonian or pseudoplastic behavior. Oil viscosity increased significantly with frying time and the degree of hydrogenation. First order kinetic models can be used to describe viscosity development.
4. FFA content increased significantly with frying time and the degree of hydrogenation. Linear models can describe the development of FFA content.
5. Dielectric property has a strong correlation with frying time and viscosity and increased with increasing frying time.

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V. CONCLUSIONS AND RECOMMANDATIONS

5.1 GENERAL CONCLUSIONS

In this study, the physical and chemical changes of fried chicken nuggets and different oil mixtures in deep-fat frying were investigated. Based on the experimental data and related analysis and discussion, we can make the following interpretations and draw the following conclusions:

i. Oil types and frying time have a significant effect on the quality properties of fried chicken nuggets, namely surface colour, texture, oil and moisture content.

ii. Colour indices (L^* and C^*) can be described by empirical first-order kinetic models. Increasing of the frying time apparently decreased lightness while the redness, yellowness and chroma increased. Fried in oils with a higher degree of hydrogenation, chicken nuggets were apparently lighter, while lower-degree hydrogenated oils may produce deeper-coloured chicken nuggets.

iii. Increasing of the frying time caused an increase in the maximum load values. The maximum loads increased with increasing of the degree of hydrogenation.

iv. The changes of oil and moisture content of fried chicken nuggets fitted first-order kinetic models. Oil and moisture contents show a negative correlation and they significantly decreased with increasing degree of hydrogenation.

v. Frying times and oil types had significant effect on oil colour, viscosity, FFA content and dielectric property.

vi. All types of oils darken during frying, as reflected by redness (a^*), yellowness (b^*), chroma (C^*) and transmittance. With increasing frying time, a^* and transmittance percent decreased while b^* and C^* increased. With the increase of the degree of hydrogenated oil, a^* and b^* increased. All colour indices can be described with the first order kinetic models.

vii. At 25°C, oil samples showed a non-Newtonian or pseudoplastic behavior. Oil viscosity increased significantly with frying time and the degree of hydrogenation. First order kinetic models can be used to describe viscosity development.

viii. FFA content increased significantly with frying time and the degree of hydrogenation. Linear models can describe the development of FFA content.

ix. Dielectric property has a strong correlation with frying time and viscosity and increased with increasing frying time.

5.2 RECOMMENDATIONS

Further researches are recommend to focus on the following three parts:

For frying oil, it should incorporate more thorough exploration of physical, chemical changes, for example, triglyceride, total polar materials, heat capacity and oil stability index, etc. In addition, it is necessary to prolong the heat time; otherwise the changes may not be significant.

More advanced testing methods should be applied to determine the moisture and fat contents in various portions of chicken nuggets, for example Differential Scanning Calorimetry (DSC). From the literature, DSC can rapidly determine fat and moisture contents. And DSC can also be used to determine the glass transition temperature that can offer a comparatively accurate storage temperature and provide valuable information to predict the storage period.

Furthermore, we can try to find the relationship among all of these parameters, and build some model to describe the dynamics between oil quality and fried food quality. For example, to model the relationship between different frying oils and pore development, pore structure in the fried foods.

Appendix I

ANOVA tables and Duncan's Multiple Range mean separation obtained for chicken nuggets samples data

I-A. ANOVA tables and mean separation for lightness (L^*) of fried chicken nuggets

Dependent Variable: L^*

ANOVA table for the effect of the frying treatments on Lightness

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	12777.30503	271.85755	24.35	<.0001
Error	359	4008.81831	11.16662		
Corrected Total	406	16786.12334			

R-Square= 0.88 CV=4.48

ANOVA table for the effect of time, oil types and their interaction on Lightness

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	520.69602	104.13920	9.33	<.0001
Time	7	11766.43547	1680.91935	150.53	<.0001
OT*Time	35	490.17353	14.00496	1.25	0.1588

Duncan Grouping	Mean	N	OT
A	68.0551	43	100
A	67.4084	70	40
A	67.2963	71	80
A	66.9671	71	60
B	65.4323	76	20
B	64.8292	76	0

Duncan Grouping	Mean	N	Time
A	78.8583	36	0
B	72.4631	35	0.5
C	69.4197	35	1
C	69.2081	32	1.5
D	66.8114	73	2
E	64.7733	65	3
F	61.6580	70	4
G	59.9102	61	5

I-B. ANOVA tables and mean separation for redness (a^*) of fried chicken nuggets

Dependent Variable: a^*

ANOVA table for the effect of the frying treatments on Redness

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	5365.709421	114.164030	53.34	<.0001
Error	215	460.170633	2.140329		
Corrected Total	262	5825.880055			

R-Square= 0.92 CV= 41.29

ANOVA table for the effect of time, oil types and their interaction on Redness

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	83.494609	16.698922	7.80	<.0001
Time	7	4919.53981	702.791402	328.36	<.0001
OT*Time	35	362.67499	10.362143	4.84	<.0001

Duncan Grouping	Mean	N	OT
A	4.2666	39	100
A	4.1300	43	80
A	3.9912	42	40
B	3.2165	43	60
B	2.9491	48	20
B	2.9254	48	0

Duncan Grouping	Mean	N	Time
A	11.3592	26	5
B	9.6766	35	4
C	6.0780	30	3
D	3.4635	34	2
E	1.1356	32	1.5
F	0.0740	35	1
G F	-0.2468	36	0
G	-0.9217	35	0.5

I-C. ANOVA tables and mean separation for yellowness (b^*) of fried chicken nuggets

Dependent Variable: b^*

ANOVA table for the effect of the frying treatments on Yellowness

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	14675.29042	312.24022	34.18	<.0001
Error	213	1945.94263	9.13588		
Corrected Total	260	16621.23306			

R-Square= 0.88 CV=9.19

ANOVA table for the effect of time, oil types and their interaction on Yellowness

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	523.31467	104.66293	11.46	<.0001
Time	7	13214.6021	1887.80031	206.64	<.0001
OT*Time	35	937.37359	26.78210	2.93	<.0001

Duncan Grouping	Mean	N	OT
A	34.6302	43	80
A	33.9331	39	100
A	33.6010	40	40
A	33.5560	43	60
B	31.0915	48	20
B	31.0867	48	0

Duncan Grouping	Mean	N	Time
A	41.3308	26	5
A	40.8817	35	4
B	38.8980	30	3
C	36.2100	34	2
D	32.7672	32	1.5
E	29.5451	35	1
F	26.3854	35	0.5
G	19.8332	34	0

I-D. ANOVA tables and mean separation for chroma (C^*) of fried chicken nuggets

Dependent Variable: C^*

ANOVA table for the effect of the frying treatments on C^*

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	10150.84792	215.97549		<.0001
Error	96				
Corrected Total	143	10150.84792			

ANOVA table for the effect of time, oil types and their interaction on C^*

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	538.082223	107.616445		<.0001
Time	7	9406.776304	1343.825186		<.0001
OT*Time	35	205.989395	5.885411		<.0001

Duncan Grouping	Mean	N	OT
A	35.87	24	100
B	35.63	24	60
C	35.55	24	40
D	33.55	24	80
E	31.40	24	20
F	31.36	24	0

Duncan Grouping	Mean	N	Time
A	43.86	18	5
B	42.33	18	4
C	40.07	18	3
D	36.58	18	2
E	33.27	18	1.5
F	30.05	18	1
G	26.44	18	0.5
H	18.54	18	0

I-E. ANOVA tables and mean separation for texture of fried chicken nuggets

Dependent Variable: texture

ANOVA table for the effect of the frying treatments on texture

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	5670.349403	120.645732	53.42	<.0001
Error	161	363.590167	2.258324		
Corrected Total	208	6033.939569			

R-Square= 0.94 CV= 13.6

ANOVA table for the effect of time, oil types and their interaction on texture

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	145.91	29.181445	12.92	<.0001
Time	7	5476.97	782.424736	346.46	<.0001
OT*Time	35	47.469023	1.356258	0.60	0.9613

Duncan Grouping	Mean	N	OT
A	12.4564	39	100
B	11.5976	42	80
C	10.8286	35	0
C	10.4871	31	40
C	10.2917	30	60
C	10.1250	32	20

Duncan Grouping	Mean	N	Time
A	16.7750	24	5
B	15.8304	23	4
C	14.1778	27	3
D	13.0304	23	2
D	12.2259	27	1.5
E	11.2768	28	1
F	8.5095	21	0.5
G	1.0000	36	0

I-F. ANOVA tables and mean separation for oil content (OC) of fried chicken nuggets

Dependent Variable: OC

ANOVA table for the effect of the frying treatments on OC

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	0.15177643	0.00322929		<.0001
Error	96				
Corrected Total	143	0.15177643			

ANOVA table for the effect of time, oil types and their interaction on OC

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	0.01355950	0.00271190		<.0001
Time	7	0.12078073	0.01725439		<.0001
OT*Time	35	0.01743621	0.00049818		<.0001

Duncan Grouping	Mean	N	OT
A	0.2088	24	0
B	0.2021	24	20
C	0.2016	24	60
D	0.1997	24	40
E	0.1874	24	80
F	0.1803	24	100

Duncan Grouping	Mean	N	Time
A	0.2321	18	5
B	0.2180	18	4
C	0.2157	18	3
D	0.2120	18	2
E	0.2028	18	1.5
F	0.1882	18	1
G	0.1656	18	0.5
H	0.1389	18	0

I-G. ANOVA tables and mean separation for moisture content (MC) of fried chicken nuggets

Dependent Variable: MC

ANOVA table for the effect of the frying treatments on MC

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	14.56052166	0.30979833		<.0001
Error	96				
Corrected Total	143	14.56052166			

ANOVA table for the effect of time, oil types and their interaction on MC

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	0.23074268	0.04614854		<.0001
Time	7	14.19554139	2.02793448		<.0001
OT*Time	35	0.13423759	0.00383536		<.0001

Duncan Grouping	Mean	N	OT
A	1.449	24	0
B	1.448	24	20
C	1.414	24	60
D	1.398	24	40
E	1.364	24	100
F	1.341	24	80

Duncan Grouping	Mean	N	Time
A	2.101	18	0
B	1.564	18	0.5
C	1.473	18	1
D	1.400	18	1.5
E	1.336	18	2
F	1.214	18	3
G	1.099	18	4
H	1.032	18	5

Appendix II

ANOVA tables and Duncan's Multiple Range mean separation obtained for frying oil samples data

II-A. ANOVA tables and mean separation for redness (a^*) of frying oil

Dependent Variable: a^*

ANOVA table for the effect of the frying treatments on redness

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	8.51340686	0.18113632		<.0001
Error	96				
Corrected Total	143	8.51340686			

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

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	2.71342639	0.54268528		<.0001
Time	7	5.51447756	0.78778251		<.0001
OT*Time	35	0.28550292	0.00815723		<.0001

Duncan Grouping	Mean	N	OT
A	-0.990	24	100
B	-1.106	24	80
C	-1.173	24	60
D	-1.179	24	40
E	-1.240	24	20
F	-1.441	24	0

Duncan Grouping	Mean	N	Time
A	-0.837	18	0
B	-0.970	18	2
C	-1.082	18	5
D	-1.193	18	8
E	-1.273	18	11
F	-1.343	18	14
G	-1.383	18	17
H	-1.424	18	20

II-B. ANOVA tables and mean separation for yellowness (b^*) of frying oil

Dependent Variable: b^*

ANOVA table for the effect of the frying treatments on yellowness

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	203.8493244	4.3372197		<.0001
Error	96				
Corrected Total	143	203.8493244			

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

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	55.9524316	11.1904863		<.0001
Time	7	135.800133	19.4000190		<.0001
OT*Time	35	12.0967595	0.3456217		<.0001

Duncan Grouping	Mean	N	OT
A	4.005	24	0
B	2.809	24	20
C	2.632	24	40
D	2.583	24	60
E	2.352	24	80
F	2.005	24	100

Duncan Grouping	Mean	N	Time
A	4.137	18	20
B	3.886	18	17
C	3.474	18	14
D	2.861	18	11
E	2.471	18	8
F	2.020	18	5
G	1.669	18	2
H	1.329	18	0

II-C. ANOVA tables and mean separation for chroma (C^*) of frying oil

Dependent Variable: C^*

ANOVA table for the effect of the frying treatments on C^*

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47		4.386	Infty	<.0001
Error	96				
Corrected Total	143	206.14			

ANOVA table for the effect of time, oil types and their interaction on C^*

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	58.1406144	11.6281229		<.0001
Time	7	138.86	19.84		<.0001
OT*Time	35	9.1415367	0.2611868		<.0001

Duncan Grouping	Mean	N	OT
A	4.281	24	0
B	3.093	24	20
C	2.895	24	40
D	2.835	24	60
E	2.606	24	80
F	2.238	24	100

Duncan Grouping	Mean	N	Time
A	4.519	18	20
B	4.126	18	17
C	3.608	18	14
D	3.143	18	11
E	2.746	18	8
F	2.282	18	5
G	1.933	18	2
H	1.575	18	0

II-D. ANOVA tables and mean separation for transmittance of frying oil

Dependent Variable: transmittance

ANOVA table for the effect of the frying treatments on transmittance

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	3.76184375	0.08003923		<.0001
Error	96	0.00000000	0.00000000		
Corrected Total	143	3.76184375			

ANOVA table for the effect of time, oil types and their interaction on transmittance

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	0.38455625	0.07691125		<.0001
Time	7	3.00389375	0.42912768		<.0001
OT*Time	35	0.37339375	0.01066839		<.0001

Duncan Grouping	Mean	N	OT
A	8.485	24	20
B	8.364	24	80
C	8.364	24	100
D	8.354	24	40
E	8.340	24	0
F	8.330	24	60

Duncan Grouping	Mean	N	Time
A	8.573	18	0
B	8.525	18	2
C	8.480	18	5
D	8.417	18	8
E	8.348	18	11
F	8.297	18	14
G	8.203	18	17
H	8.138	18	20

II-E. ANOVA tables and mean separation for viscosity of frying oil

Dependent Variable: viscosity

ANOVA table for the effect of the frying treatments on viscosity

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	0.00405427	0.00008626	419.50	<.0001
Error	38	0.00000781	0.00000021		
Corrected Total	85	0.00406209			

R-Square= 0.998 CV= 0.64

ANOVA table for the effect of time, oil types and their interaction on viscosity

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	0.00349606	0.00069921	3400.38	<.0001
Time	7	0.00069058	0.00009865	479.77	<.0001
OT*Time	35	0.00000000	0.00000000	0.00	1.0000

Duncan Grouping	Mean	N	OT
A	0.0837125	12	100
B	0.0756015	13	80
C	0.0701256	16	60
D	0.0672337	19	40
E	0.0652514	14	0
F	0.0642217	12	20

Duncan Grouping	Mean	N	Time
A	0.0768536	11	20
B	0.0725618	11	17
C	0.0706700	8	11
D	0.0700036	11	14
D	0.0697617	12	8
D	0.0696350	12	5
E	0.0679745	11	0
F	0.0671550	10	2

II-F. ANOVA tables and mean separation for FFA of frying oil

Dependent Variable: FFA

ANOVA table for the effect of the frying treatments on FFA

Source	DF	Squares	Mean Square	F Value	Pr > F
Model	47	5.37424923	0.11434573	535.79	<.0001
Error	82	0.01750000	0.00021341		
Corrected Total	129	5.39174923			

R-Square= 0.996   CV= 2.59

ANOVA table for the effect of time, oil types and their interaction on FFA

Source	DF	SS	Mean Square	F Value	Pr > F
OT	5	0.41614902	0.08322980	389.99	<.0001
Time	7	2.75760473	0.39394353	1845.91	<.0001
OT*Time	35	2.20049548	0.06287130	294.60	<.0001

Duncan Grouping	Mean	N	OT
A	0.635476	21	20
B	0.605227	22	40
C	0.587955	22	60
D	0.567750	20	80
E	0.542857	21	100
F	0.462083	24	0

Duncan Grouping	Mean	N	Time
A	0.734167	18	20
B	0.718750	16	14
C	0.657353	17	17
D	0.634375	16	11
E	0.567188	16	8
F	0.483929	14	5
G	0.380000	15	2
H	0.325000	18	0