Oil absorption during deep-fat frying: mechanisms and important factors

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OIL ABSORPTION DURING DEEP-FAT FRYING: MECHANISMS AND IMPORTANT FACTORS

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To my wife **Ailar** and

my children **Dayan** and **Ilay**

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Publications & Communications

Publications

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Communications

1. ZIAIIFAR A.M., COURTOIS F., and TRYSTRAM G., April 2008. Variation of porosity during frying and cooling of French fries and its relation with oil absorption. Oral presentation & Poster, *International Congress of Engineering and Food (ICEF10) Chile.*

2. ZIAIIFAR A.M., HEYD B., and COURTOIS F., April 2008. Investigation of heat conductivity variation of crust and core regions of fried potato using modified Lees method, Poster presentation, *International Congress of Engineering and Food (ICEF10) Chile.*

3. ZIAIIFAR A.M., COURTOIS F., and TRYSTRAM G. September 2008. Investigation of oil physical properties affecting oil absorption during frying process. Oral presentation, *6th Euro Fed Lipid Congress, Greece.*

Structure of the thesis

Chapter one: Summary of the thesis

Chapter Two: Literature reviews

Part 1: Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process

Part 2: Modeling of heat and mass transfer during deep-fat frying: a review

Chapter three: Results

Part 1: Porosity development and its effect on oil uptake during frying process

Part 2: Oil absorption during cooling of French fries: experimental study

Part 3: Investigation of effective thermal conductivity kinetics of crust and core regions of potato during deep fat frying using modified Lees method

Table of contents

List of figures

Chapter 1:

Chapter 2 part 1:

Chapter 2 part 2:

Chapter 3 part 1:

Chapter 3 part 2:

Chapter 3 part 3:

List of tables

Chapter 1:

Chapter 2 part 1:

Chapter 2 part 2:

Chapter 3 part 1:

Chapter 3 part 2:

No table

Chapter 3 part 3:

Chapter 1

Summary of the thesis

Chapter one: Summary of the thesis

1. Introduction

Frying is considered to be one of the oldest methods of food preparation due to high cooking rates and desirable product characteristics. It is a unit operation which is mainly used to alter the eating quality of a food. Deep-fat frying involves immersion of food in hot edible oil at a temperature above the boiling point of water for a given period of time (Farkas *et al.*, 1996). The process involves both mass transfer, mainly represented by water loss and oil uptake, and heat transfer (Vitrac *et al.*, 2002). Deep-fried foods are now popular for their distinct flavor and texture, as evidenced by the multi-billion dollar market products. Recent trends in the worldwide consumption of potatoes show that frozen French fries have contributed to enormous expansion of international trade in this commodity, a 16-fold increase between 1980 and 2001 (FAO, 2006).

The attainment to a high and constant quality of fried products with appropriate oil content is of considerable interest to food industry and consumers. Fat uptake is considered the major nutritional critical point of deep-fat frying because of the obesity and the negative effects of excess oil consumption on human health. This point has caught the attention of researchers. In recent years, there has been a strong encouragement to reduce oil content of fried foods, prompting many researches on the development of food products that have reduced fat and cholesterol levels. There is a need to develop a better understanding of how oils are absorbed by foods that are deep-fried and how the processing conditions influence the quantities absorbed. The main challenge is therefore to improve the frying process by controlling and lowering the final oil content of the fried product.

2. Hypothesis of the study

This research is based on the hypothesis that oil uptake is influenced principally by the porous structure of product (porosity) and the oil absorption takes place mainly when the product is removed from fryer (cooling period). The assumption is that the fundamental pore formation is the result of water loss from the product forming capillary channels, which subsequently serves as pathways for oil intake into the product during cooling period. It was decided to investigate the effect of frying oil temperature, frying time, chemical-physical changes and thermal properties of French fries on oil uptake. This study was based on potato French fries while used methods and treatments can be applicable to other fried foods. The scope of this study is to measure the porosity using liquid and helium displacement pycnometry, the heat conductivity using modified Lees method and a closer study of cooling condition, regarding oil absorption.

3. Objectives

This research was performed to better understand the oil absorption in deep-fat fried product. Past research has focused on the oil absorption during frying period. This study will add new insight to the oil absorption that is the oil absorption and porosity changes not only during frying but also during cooling period. The main objectives of this research, based on the hypothesis, were to determine and quantify the porosity of French fries during two successive periods of frying process (frying and cooling periods) and to study the kinetics of thermal conductivity in the crust and core regions during frying. The specific objectives are listed as follows:

1. To review the important mechanisms and factors involved in oil uptake and to study the different literature models in frying,
2. To establish the relationship between oil uptake and moisture loss during deep-fat frying at different oil temperatures,
3. To determine the apparent and absolute densities of fried products as a function of time and moisture loss,
4. To study the relationship between oil uptake and porosity changes,
5. To study the kinetics of the thermal conductivity of crust and core regions

4. Outline of the study

4.1. Introducing the different parts of this thesis

Complexity of oil absorption phenomenon during frying process, combined with structural changes and lack of information on porosity variation and oil uptake during cooling period, has promoted the research described in this thesis. The results obtained in this research were in the form of papers published or accepted for publication or in preparation; therefore, it was decided to prepare a thesis based on the papers. This thesis is based on the following five papers:

1. Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process, *International Journal of Food Science and Technology (published).*
2. A review of published models on deep-fat frying process *(in preparation).*
3. Porosity development and its effect on oil uptake during frying process, *Journal of Food Process Engineering (in press).*
4. Oil absorption during cooling of French fries: experimental study. (i*n preparation*).
5. Investigation of heat conductivity variation of crust / core regions of fried potato using modified Lees's method. *Journal of Food Engineering (submitted).*

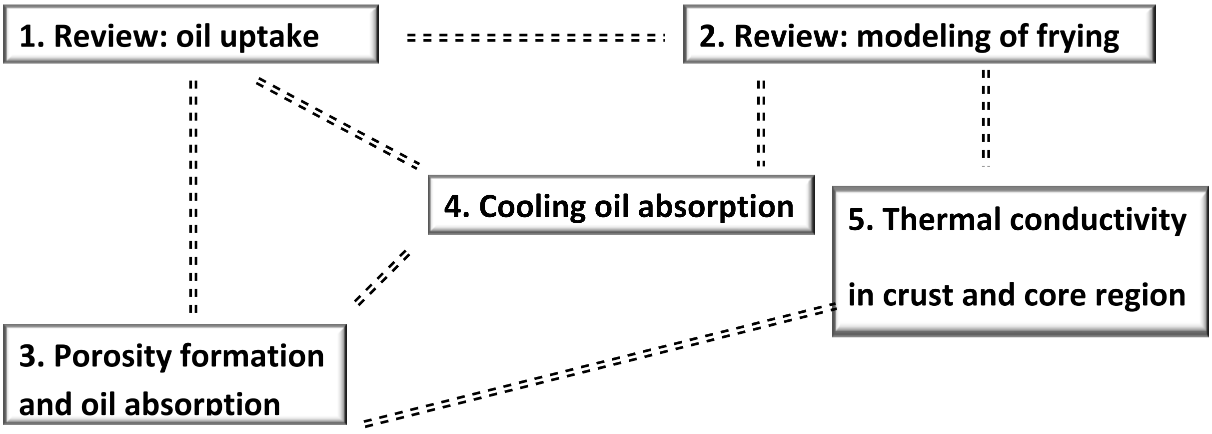

Figure 1. The relation between different parts of the thesis

This study consists of two main contents. The primary (papers 1, 3 and 4) discusses the oil absorption phenomenon and the important factors which affect this phenomenon. The second part (papers 2 and 5) reviews the models of frying process and discusses the thermal conductivity of different sections of product. The results discussed in this thesis permitted us to make the following conclusions and interpretations.

Paper 1 reviews the different mechanisms and important parameters in oil absorption. The positive or negative effects of each parameter on final oil content were particularly discussed. This review confirmed that the oil absorption during frying process is resulting from a mix of complex phenomena. The most important elements responsible to the complexity of oil uptake phenomena can be listed as:

- Simultaneous heat and mass transfers,
- Porous structure of product during frying,
- Changes in mechanisms of transport
- Changes in product properties,

The mechanisms involving in oil absorption are subject of contradiction in literature. Vitrac *et al*. (2000) showed that during frying period, an overpressure of 45 kPa inside the food was assessed which prevented any migration of oil inside the material. However, during cooling period, oil penetration is no longer affected by this mechanism. In addition, the rapid temperature decrease in crust (a hygroscopic domain) may generate an immediate condensation of steam which is responsible of pressure drop down. While they stated that the vacuum effect due to steam condensation is the most important force acting on oil uptake in the porous media, Moreira *et al*. (1997) proposed the capillary pressure as the major factor in oil absorption. They showed experimentally that tortilla chips took most of the oil during the first 20 s of cooling when the chips' inner temperature is above that of water condensation. This observation leads to the conclusion that oil uptake during the cooling period takes place by capillary force rather than by vapor condensation. This point can be clarified by further studies on the starting time and the duration of oil absorption. If all of adhered oil is absorbed in the early stage of cooling, the capillary pressure only can explain the oil uptake. On the other hand if the oil is absorbed continuously even when the product temperature decreases below the vapor condensation temperature, the vacuum effect and the capillary pressure, both, play a role in oil absorption.

The review (paper 1) showed the importance of pore formation on oil absorption. This point conducted us to study the porosity of fried product and its relation with oil absorption (paper 3). The review also showed that the oil is absorbed during cooling period rather than frying period. Therefore we carried out a deeper study on the conditions of cooling period in order to better understand the oil absorption phenomenon (paper 4).

Paper 2 presents a review of the modeling of heat and mass transfer during frying process. The objective was to better understand the heat and mass transfer during frying process. The main objective was to optimize the frying process by understanding the oil absorption phenomenon. The modeling of frying process will be better when the meaningful data of affecting physical and thermal properties are available. The need for these data was highlighted during the International Congress of Engineering and Food (ICEF 10) in Chile. This was the reason why the experimental works in paper 5 were carried out. In this paper, the kinetics of thermal conductivity was investigated in crust and core of fried product.

The most important aspects of frying, discussed through this study in order to decrease the oil content of product, were:

- Oil absorption
    - How (by which mechanisms) oil enters into the product (paper 1 and 2, and 4)
    - When the oil is absorbed by product (paper 4)
    - Where the absorbed oil is located in the product (paper 3)
- Properties:
    - What are the important oil properties influencing the oil absorption (paper 4)
    - What are the product properties affecting oil absorption (paper 1 and 3)
- Processes:
    - What are the effects of raw material pre-treatments before frying (paper 1)
    - Which are the main factors affecting oil absorption during frying process (paper 3)
    - What are the effects of product post-treatments after frying (paper 4)
- Modeling of frying process (paper 2)
    - Which are the physical properties affecting the oil absorption (paper 3 and 4)
    - Which are the thermal properties affecting oil uptake (paper 2 and 5)

4.2. Porous structure of fried food

The relationships between changes in food microstructure due to deep-frying and food quality are very important, yet still not well understood. However, information on pore development and the evolution of pore during deep-fat frying may shed light on these relationships and lead to strategies that simultaneously ensure adequate heating for food safety assurance, and yield final products with the taste and textural characteristics expected by the consumer. Physical properties, such as density, shrinkage and porosity, are the main factors affecting the texture and transport phenomena of fried foods. Few experimental works have been carried out on porosity variation during the full frying process (frying and cooling) especially concerning the cooling period, which is critical for oil uptake. For this raison, the experimental studies of paper 3 were carried out. These studies permitted us to better understand how the mechanism of oil absorption during deep-fat frying may change from the beginning of the process to the cooling stage.

4.2.1. Mechanisms of pore development

The escape of moisture by vaporization results in the creation of paths, usually referred to as capillary pores (Gamble and Rice, 1987; Ufheil and Escher, 1996), through which hot oil enters the food. In fact, as dehydration occurs at a temperature above 100°C, water steam finds selective weaknesses in the cellular adhesion that leads to the formation of capillary pathways increasing surface porosity. Furthermore, some of this vapor may be trapped within the pores due to restrictive intercellular diffusion and expand, becoming superheated, distorting the pore walls and contributing to more formation of pores.

4.2.2. Factors influencing the product porosity

The two important phenomena in porosity variations are surface rupture and collapse in the product. Surface rupture takes place when the product is in the hot oil and results from increasing internal pressure of the core region because of the heating process. Surface rupture increases the porosity leading to more oil uptake. Collapse probably takes place during the cooling of products when water evaporation is stopped and a vacuum is formed. Collapse takes place in this state because the food matrix can no longer hold itself and collapses under the force of gravity. This phenomenon decreases the porosity.

The porosity changes significantly with moisture content. Higher bath temperatures cause faster pore formation because of accelerated water evaporation during the frying period; this condition increases the porosity. This result can be explained by water loss, apparent density decrease and crust formation. During the cooling period, because of oil filling and collapse, the porosity decreases. Pores can be filled with oil, water vapor or a mixture of the two depending on the periods of the frying process (frying and cooling periods). During the cooling period, the created pores are filled by oil and partly closed by the collapse phenomenon.

4.2.3. Densities variations during frying process

During the frying period, the apparent density decreases. The decrease in the apparent density has been related to the combination of pore formation (puffing of sample), water loss and oil uptake. In contrast, during the early stage of cooling, the apparent density of the samples increases. During frying period, the absolute density increases while it remaines unchanged during the cooling period. The reason for this stationary behavior of absolute density may depend on two phenomena, which take place during cooling: collapse in isolated pores and oil absorption.

4.3. Towards modeling of frying process: accessing important properties

Paper 2 reviews several models which have been developed for heat and mass transfer during frying process in literature. Models to describe frying process are needed for engineering design and optimization. The theoretical aspects of the frying process are highly complex and difficult to understand. Frying process should be described as a coupled heat and mass transfer resulting in the displacement of a moving vaporization front that separates two dynamic regions: a dehydrated crust and a humid core. Some models do not take into account the cooling period for oil absorption while the others are based on both periods of frying process i.e. frying and cooling. Moisture transport takes place by different mechanisms as: diffusion gradient, capillary flow, Darcy flow and vapor convection flow.

4.3.1. Physical properties

Studies reported in literature have shown that the oil absorption takes place from the adhered surface oil into the product mainly when it is removed from fryer. Therefore, the physical properties of adhered oil at the surface of the fried product were investigated in order to understand the conditions in which this oil is absorbed (paper 4). The temperature is the main factor influencing the cooling condition and oil absorption. Indeed, the physical properties of oil and product such as the oil viscosity, oil density, interfacial tension (between oil and product) and vapor pressure in the food material, which play roles in oil absorption, all, are influenced by temperature.

Interfacial tension, which is influenced by temperature, measures the degree of interaction between the oil and the food material. During cooling period, when the surface oil temperature tends to decrease, the oil interfacial tension increases, resulting in more oil absorption of product. The product pores are filled with water vapor and not with air because air escapes from the product during frying period. Therefore, in order to obtain more meaningful data in model simulation of oil absorption phenomena, the interfacial tension between oil and water vapor rather than oil and air should be investigated (paper 4).

Oil viscosity determines the thickness of adhered oil at the surface of fried product; the higher viscosity the thicker the adhered oil layer and lessen oil drainage when the product is removed from fryer. On the other hand, it determines the oil flow into the product during cooling period. Therefore, the oil viscosity plays a contradictory role in oil absorption. It seems that the positive effect of higher viscosity is much higher than its negative effect (paper 4).

4.3.2. Thermal properties

Among the thermal properties relevant to process modeling, thermal conductivity is one of the most determining factors. The thermal conductivity of food materials depends on its porosity, structure and chemical constituents. The knowledge of the value of thermal conductivity of different regions in fried products is needed for mathematical modeling of frying process. In literature, the thermal conductivity has been studied on whole product, while some products (such as potato), when fried, present two regions being different in physical and thermal properties: core being humid and soft and crust having a dry and rigid structure.

The kinetics of thermal conductivity in crust and core regions were not readily available in literature and the use of approximate values lowers the accuracy of model output. Crust and core regions of fried products represent different structural properties. Crust formation is the result of changes in the structure of the outer tissue of potato after exposure to hot oil, namely, softening of the middle lamella between cells, starch gelatinization inside cells, and dehydration. The most important physical change in core region is starch gelatinization. Starch gelatinization can be considered as the only affecting factor in core thermal conductivity increase in core region during the first minutes of frying. Later, the decrease in thermal conductivity can be related to the moisture loss; during this stage the moisture content decreases.

The effect of thermal conductivity of the crust is very important in frying process since it controls the process. Heat must be conducted through the crust with low thermal conductivity. The crust thermal conductivity is lower than core due this fact that it contains lower moisture content and presents more porous medium when compared with core. In crust, the moisture content decreases with frying time, decreasing its thermal conductivity. With the same moisture content the top crust thermal conductivity is lower than bottom crust. This point can be explained by this fact that top crust is generally separated from core region after certain time of frying due to the water evaporation and represents a net crust (visual observation). While the bottom crust sticks to the core region during frying and may include an intermediate section between crust and core.

4.4. Factors affecting final oil content of French fries

Summary of the important factors in final oil content of French fries, which were highlighted in literature, were listed in table 1 and the related causes were discussed in each case.

Table 1. Factors involved in final oil content of French fries (↑ is "increases oil content"; ↓ "decreases oil content", ↕ "Contradictory in literature").

	1. Raw materials selection				**2. Pre-treatments**					
	Potato properties		***Oil physical properties***		***Mechanical treatment***	***Thermal treatment***			***Surface treatment***	
Parameter	Moisture content	Porosity	Viscosity	Interfacial tension	Cutting	Blanching	Steam baking	Osmotic dehydration	Pre-drying	Coating
Effect	↑	↑	↑	↑	↑	↕	↓	↕	↓	↓
Why this effect?	1	2	3	4	5	6	7	8	9	10

Table 1 (continued)

3. Frying process								
Frying period conditions			***Cooling post-treatments***					
Temperature	Pressure	Time	Removing speed	Shaking	Centrifuge treatment	Vacuum cooling	Hot air treatment	Steam treatment
↑	↑	↑	↓	↓	↓	↓	↓	↓
11	12	13	14	15	16	17	18	19

1. The higher moisture content in raw potato induces more water loss and formation of more porous material. This fact increases oil content of product.
2. Product initial porosity increases the oil absorption. Indeed, more porous product absorbs more oil during the frying process.
3. Oil viscosity determines the thickness of adhered oil at the surface of fried product; the higher viscosity the thicker the adhered oil layer.
4. Interfacial tension between oil and air increases the oil uptake flow according to the capillary action.

5. Cutting increases the surface roughness and contact surface area of raw potato with the oil, increasing oil absorption.

6. Blanching decreases the dry mass content of the product increasing final oil content. On the other hand, surface starch gelatinization that occurs during blanching could form a firm thin layer that protects the food from oil absorption.

7. Steam baking can be used to form a tight barrier at the outer surface of the product because of severe starch gelatinization. This outer layer presents strong resistance to oil entrance into the product.

8. Osmotic dehydration is a partial dehydration by immersion of the raw product in a concentrated solution usually sugar. In the literature, its effect on oil absorption is contradictory. While some authors had stated that osmotic dehydration decreases oil content by decreasing the initial water content of the product and formation of a layer around the surface of product, the study done recently showed that oil uptake of osmotically dehydrated samples was even higher than the untreated samples due to the greatest space available resulting from the considerable water lost during this pretreatment.

9. Pre-drying creates a firm and dried surface around the product. This technique decreases the total water content of the product and limits oil absorption.

10. Coating reduces surface permeability and builds a barrier against oil absorption.

11. High frying temperatures limit frying time resulting less oil content.

12. There was more than 55% oil reduction when potato slices were fried under vacuum frying compared with oil content of conventional frying.

13. Generally, the longer the product remains in the fryer; therefore, the more the oil is absorbed.

14. The faster the products pick up, the thinner the adhered surface oil. This fact decreases final oil content.

15. Shaking the product when removed from fryer decreases the surface unabsorbed oil resulting in lower oil content.

16. The centrifuge force during cooling period removes the surface oil and also to some extent the absorbed oil.

17. Vacuum cooling decreases oil content of fried product due to non-stop water evaporation during the early stage of cooling which causes more oil drainage from the surface of product.

18. Hot air treatment maintains the product temperature and prevent cooling, thus partially preventing the steam condensation and vacuum effect in oil absorption.

19. Steam treatment decreases the surface oil resulting in less oil content.

4.5. Main conclusions

Based on experimental data and the related discussions, we can draw the following main conclusions:

- Oil uptake phenomenon takes place by a combination of mechanisms. The capillary effect (primary) and the vacuum effect (secondary) are the main mechanisms in oil absorption.
- The product porosity can be the place of oil absorption so it determines the capacity of oil absorption. The development of porous media and oil absorption are not synchronized, i.e., oil enters mainly during the cooling period and partially fills the locations (pores), which were created when the product is still in the hot oil.
- During the frying period, the absorbed oil content is not enough to fill the pores, which are continuously forming. While during cooling period, the pores are mostly filled by oil. It is believed that the collapse also plays an important role in porosity decrease because the volume of the absorbed oil is low to explain the decrease in porosity.
- The oil fills some spaces created by water loss. Only 5–14% of evaporated water is replaced by oil, showing this fact that the oil that can be absorbed by French fries is limited mainly to the remaining oil at the surface of product when removed from fryer.
- The effect of frying temperature on final oil content of fried product is contradictory in literature. Our results showed that low temperatures leads to more oil content (about 30%) in French fries. During frying at low temperatures, oil absorption takes place not only during the cooling period but also to some extent during the frying period leading to more oil content.
- Two important treatments in order to decrease the oil content of fried product are centrifugation and vacuum cooling. The centrifugation can considerably decrease the oil content of product while the effect of vacuum cooling was lower.
- A modified Lees method can be successfully used to measure the effective thermal conductivity in different parts (core and crust) of fried potato. Thermal conductivities in

the crust and core regions don’t follow the same kinetic. The core thermal conductivity increases at the early stage of frying due to gelatinization of starch, and reaches a maximum value. Then it decreases due to moisture loss. In the crust region the starch gelatinizes at the early stage of frying (first seconds of frying). Its thermal conductivity decreases due to formation of porous structure and moisture loss.

Many food research projects attempt to understand oil uptake during the frying process in order to control and reduce the fat content of fried products. We hope that the results of this work lead to finding the way(s) to produce less greasy fried products.

5. Perspectives and recommendation for future work

This study has indicated that oil absorption is a complex phenomenon in which several parameters could be involved. Some important parameters have been identified but the exact mechanisms of pore formation and oil absorption is still not clear. More study must be done to produce a clearer understanding of the problem. The following are some suggested further studies:

Modeling of oil absorption phenomenon:

- The interfacial tension between oil and steam. While the data of interfacial tension between oil and air are available in literature, there is no experimental data on the interfacial tension between oil and water vapor at boiling temperature. Collecting these data would give valuable information.

- The adhered surface oil thickness. It will be interesting to question the oil film thickness formed when the product is removed from the fryer. This thickness depends on oil viscosity and the conditions of product removal.

- The pore diameter and tortuosity of crust region. As oil fills the porous structure, characterization of the porous crust region such as pore diameter and tortuosity should be more investigated. For frying oil, it should incorporate more thorough exploration of its physical properties.

A technologic suggestion:

- Intermediate period between frying and cooling. As the oil absorption takes place from the adhered surface oil when the product is removed from fryer it would be of interest to make an intermediate period in order to decrease the oil content. It is believed that a combination of vacuum and hot air, behind effective shaking can decrease drastically the final oil content of fried product.

Study on heat and mass transfer in:

- Pre-fried and frozen French fries. This research assumes that the raw material is not frozen. Whereas French fries are consumed when they are in pre-fried and frozen state. Therefore, a study on the heat and mass transfer especially oil uptake in this condition should be conducted by incorporating thawing in addition to frying.
- Pan frying. The heat and mass transfer in pan frying could be studied.

The information obtained from these additional studies would provide a better understanding of the oil absorption phenomenon, which may lead to the development of a practical solution to this important problem faced by the industry.

At the end, it is hoped that this work will make a humble contribution to the efforts to reduce oil content of fried product.

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Chapter 2

1st part:

Review of mechanisms, conditions, factors involved in the oil uptake phenomenon during the deep-fat frying process

2nd part:

Modelling of heat and mass transfer during deep-fat frying: a review

Literature reviews

Chapter Two: Literature reviews

Introducing text

In this thesis, all components were integrated into a cohesive unit with a logical progression from one chapter to the next. In order to ensure that the thesis has continuity, connecting texts that provide logical bridges preceding and following each manuscript were provided.

The second chapter of the thesis includes two literature reviews:

- review of oil absorption
- review of modeling of frying process

In the first review, the oil absorption phenomenon during the frying process was investigated. The different mechanisms which can play roles in the oil uptake were discussed. Furthermore, the important factors which are related to this phenomenon were listed. This review permitted to understand the oil absorption phenomenon. This point was very important to us to determine what kind of information and experimental works are needed in order to find the ways to reduce the oil uptake. This review encouraged us to do the experimental works in order to understand:

- Where the oil absorption takes place (paper 3). As the oil fills the pores it is decided to work on the porosity of the product during whole frying process i.e. frying in the hot oil and cooling at ambient temperature and pressure.
- When the oil is absorbed (paper 4). As highlighted in literature the cooling period is the main period in oil absorption. This was why the experimental works in order to understand what are the important factors and the conditions which play the role in oil absorption.

Part 1: Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process

Keywords: Oil uptake, deep-fat frying, water loss, condensation, capillary pressure, process parameters, product properties.

Abstract

Deep-fat frying is a rapid and low cost process widely used to prepare tasty food. During this cooking process, oil is used both as the heating medium and as an ingredient producing calorific products. Nutrition has become a major health issue, especially in developed countries where increasing obesity is a problem, particularly among children. Many food research projects involving snack food industries therefore attempt to understand oil uptake during the frying process in order to control and reduce the fat content of fried products without deteriorating their desirable organoleptic characteristics. The main objectives of this paper are to review the literature on the frying process and more precisely the mechanisms and parameters involved in the oil uptake phenomenon. Both products and processes will be considered and their influence via experimental results will be discussed.

1. Introduction

Deep-fat frying is a multifunctional operation of food transformation. This process may be defined as cooking food by immersion in edible oil or fat at a temperature above the boiling point of water (Hubbard & Farkas, 2000). It is a rapid process of simultaneous heat and mass transfers, which can be used as a drying operation. Actually, in addition to food applications, this process is used to dry meat carcasses, sewage sludge and wood to stabilize them (Vitrac, 2000; Silva *et al.*, 2005). Deep-fat frying remains a complex operation because of the two mass transfers in opposite directions within the material being fried: for starchy products, water and some soluble material escapes from the products and oil enters the food (Blumenthal & Stier, 1991). Sometimes, even fat can escape from the product in the oil bath during frying of raw material presenting a significant fat content, such as meat or fish (Oroszvari *et al.*, 2005). Moreover, during frying, the material undergoes chemical and physical transformation at a high operating temperature range of 140°C to 180°C. Finally, starting with a raw product, frying joins dehydration to cooking, with starch gelatinization, protein denaturation, aromatizing and colouring via Maillard reactions and finally oil uptake. These reactions are strongly coupled but a transformation could be privileged by adaptation and optimization of process parameters (Vitrac, 2000). Currently, fat uptake is considered the major nutritional critical point of deep-fat frying due to the epidemic obesity prevalent in developed and even in developing regions where meals high in fat and sugar are the cheapest (FAO, 2002). The main challenge is therefore to improve the frying process by controlling and lowering the final fat content of the fried products. In addition, during frying, potentially toxic neoformed compounds may appear in the oil bath as a consequence of oil deterioration due to oxygen, heat and water (Gertz, 2005). These compounds modify the physical and chemical properties of oil and can favour oil uptake. Thus, for this second reason, quality and quantity of oil uptake have to be carefully controlled. Numerous studies about oil uptake during frying have been published over the past 10 years to better understand this phenomenon. It appears that mechanisms of oil uptake have been highlighted but many contradictions on the conditions still remain due to the numerous parameters involved. In conclusion, oil uptake is a complex phenomenon resulting from interactions between oil and products that undergo numerous physical, chemical and structural transformations during frying.

This review will begin by describing fried products and experimental facts about oil location and period of oil absorption. Mechanisms of oil uptake as a consequence of the hydrothermal behaviour of the product during frying will then be presented and the interrelationships between the product and the oil will then be discussed. On the basis of this information, process parameters influencing oil absorption will be listed and possible improvements of the process will be presented.

2. Nutritional characteristics of frying products

Fried products come in a wide variety. Considering starchy products, fried food can be classified in two major technological categories: thin products, quasi totally dehydrated, such as potato, cassava or tortilla chips, and thick products such as French fries or plantain cylinders where dehydration is only partial. As a result, thin final products present a very low water content (<5%) resulting in low water activity and long shelf life. They can be easily packaged for storage and distribution. However, as thin products present a high fat content (between 30 and 40%), oil stability during storage has to be carefully managed in order not to develop off-flavours in the product. Thick products present an intermediary water content of about 30 to 50% wet basis and a relatively low fat content (inferior to 15%) and must have a crispy crust but a wet and soft centre like cooked potato (Moreira, Castell-Perez & Barrufet, 1999). These products can be made from fresh material or from frozen products that have generally been par-fried before. Par-frying consists in frying the food for a very short time to prevent enzymatic action before a freezing operation. A second frying stage is necessary to complete the cooking process. In these par-fried products, final oil content is generally higher than in freshly fried products because of the two successive frying stages. In addition, it has been proven that during frying some water soluble micronutrients (ascorbic acid and potassium) are also well preserved (Rojas *et al.*, 2006). Hence, the high temperature/short time operation at the basis of good deep fat frying practices can be of interest for conserving some final nutritional properties of the products.

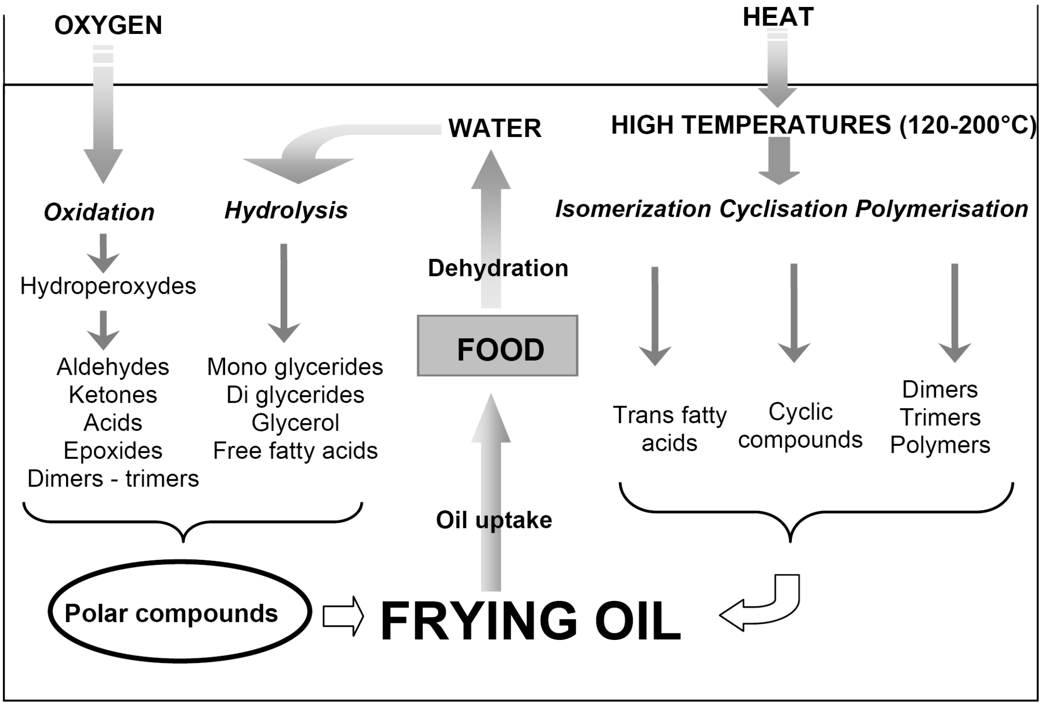

Fig. 1. Outline of the oil degradation during frying and the consequences on the product quality.

During frying, water escapes from the food while oil migrates into the food providing nutrients and flavours. Frying oils thus have the original property of being both a heat transfer medium and an ingredient of the final product representing up to 40% of the total mass in products like chips. In addition, the fatty acid composition of the oil present in the fried product does not differ from the fatty acid composition of the frying medium. Hence, the choice of a suitable oil for frying is very important, not only for its potential nutritional value but also for its ability to support frying conditions. Indeed, during frying, oil deteriorates due to heat, water, and oxygen exposure (Achir *et al.*, 2006) as shown in figure 1. The result of these complex chemical reactions is an increasing amount of lipid degradation compounds in the oil bath as free fatty acid, mono and diglycerides, polymers, potentially toxic carbonyl compounds etc. that can be further absorbed by the product, lowering its nutritional value (Gertz, 2005). Even if a frying oil regulation is established limiting polar compounds to 25% and polymer content to 12%, potentially toxic compounds can appear in the oil bath. The main hazardous compounds presently identified are potentially carcinogenic molecules such as carbonyl compounds or monoepoxides and some aldehydes produced from linoleic acid, e.g. 4-hydroxy-2-trans-nonenal that has been proven to be cytotoxic (Seppanen & Saari Csallany, 2002; Matthäus & Wöhrmann, 2006).

To assure consumption of safe frying products, good frying oils must therefore be chosen on the basis of a compromise between their thermal stability, nutritional properties and cost. The major types of oils that are produced worldwide are soybean, palm, canola, sunflower, cottonseed, peanut, palm kernel, coconut, olive and maize oils. Among them, soybean, palm, canola, and sunflower oils represent 80% of the world production (AAC, 2005). Palm oil has a high level of saturated fatty acids that is good for its thermal stability but not interesting from a nutritional point of view. On the other hand, oil presenting a high content in poly unsaturated fatty acids such as soybean, canola and sunflower oils are nutritionally interesting but are very sensitive to oxidation. Furthermore, linoleic oils like sunflower and soybean oil should be avoided because of the risk of production of 4-Hydroxy-2-trans-nonenal. Unsaturated oils can be partially hydrogenated in order to increase their chemical stability. However, trans fatty acids are a major by-product of hydrogenation and can represent 30% of the total fatty acids. Epidemiological studies have demonstrated that the intake of trans fatty acids can be correlated with the risk of cardio vascular disease (Daniel *et al.*, 2005). Therefore, ideal frying oils can be a mix of different oils presenting complementary chemical properties or can be produced from modified plants like high oleic sunflower, and high oleic canola oils. These oils have good nutritional and frying properties, are more expensive but can meet more demanding health specifications (figure 2).

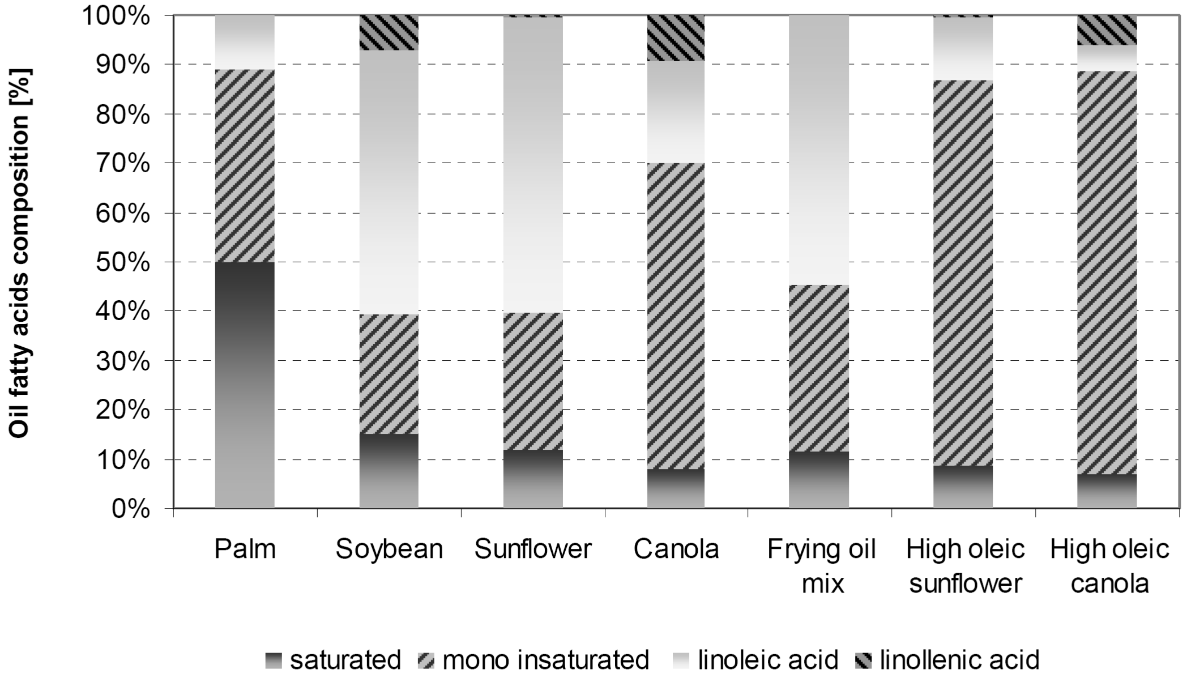

Fig. 2. Composition of frying oils (commercial data).

3. Oil location and period of oil absorption: experimental facts

Oil absorption is principally a surface phenomenon as confirmed by experimental observation: It has been shown using calorimetry (Aguilera & Gloria, 1997) that the crust of French fries contain almost 6 times as much oil as the inner part. Keller *et al.* directly visualized fat distribution in French fries by carrying out the frying process in dyed oil (Keller *et al.*, 1986). They concluded that the frying oil remained on the porous surface region of the French fries and particularly in the first cell layers. Moreira and Barrufet added that oil concentrates around the edges and in the puffed areas (Moreira & Barrufet, 1996). Using nuclear resonance imaging on alginate gels fried at 170°C, Vitrac (2000) confirmed the existence of two distinct regions: a central region saturated with water and a dried crust receptacle of oil. More recently, Lisinska & Golubowska (2005) used electron scanning microscopy to follow potato structural transformation during the production of French fries and confirmed that oil was mainly located in the surface of potatoes where cells undergo maximum deformation. With the same technique, Vitrac (2000) noticed the development of a heterogeneous porous structure in cassava chips. Confocal observations made by Pedreschi *et al.* (1999) showed that oil enveloped the surface of potato cells like an "egg-box" and was mainly trapped in voids due to cell rupture during cutting. Oil did not, however, penetrate the intact cells because of the composition of potato parenchyma. Indeed, the cell wall is thicker and stronger than the middle lamella shared with surrounding cells. Therefore, cell separation occurs rather than cell rupture. Aguilera *et al.* (2001) made complementary explanations after "hot stage" microscopic observations of isolated potato cells during frying. They explained that during frying, starch gelatinization and swelling occur very rapidly, thus making potato cells with a dense starchy interior capable of supporting dehydration with shrinkage but with no cell rupture. To conclude, oil does not penetrate into cells but enters voids resulting from the breakdown of adhesive forces between cells when water is removed from the product.

This phenomenon is illustrated by figure 3 where the surface cells of potato observed under confocal microscopy are obviously deformed during frying and different holes can be created between cells. Miri *et al.* (2006) used a non invasive technique, X-Ray tomography, to observe the porous structure of potato cylinders during frying at 170°C. Using imagery techniques, they reconstituted and characterized the crust structure (i.e. its thickness, porosity and interconnectivity of pores) and concluded that the crust was formed mainly during the final minutes of frying. In addition, interconnectivity between the pores was found to be limited and fried potato porosity was identified as being due to a few large pores rather than to small ones.

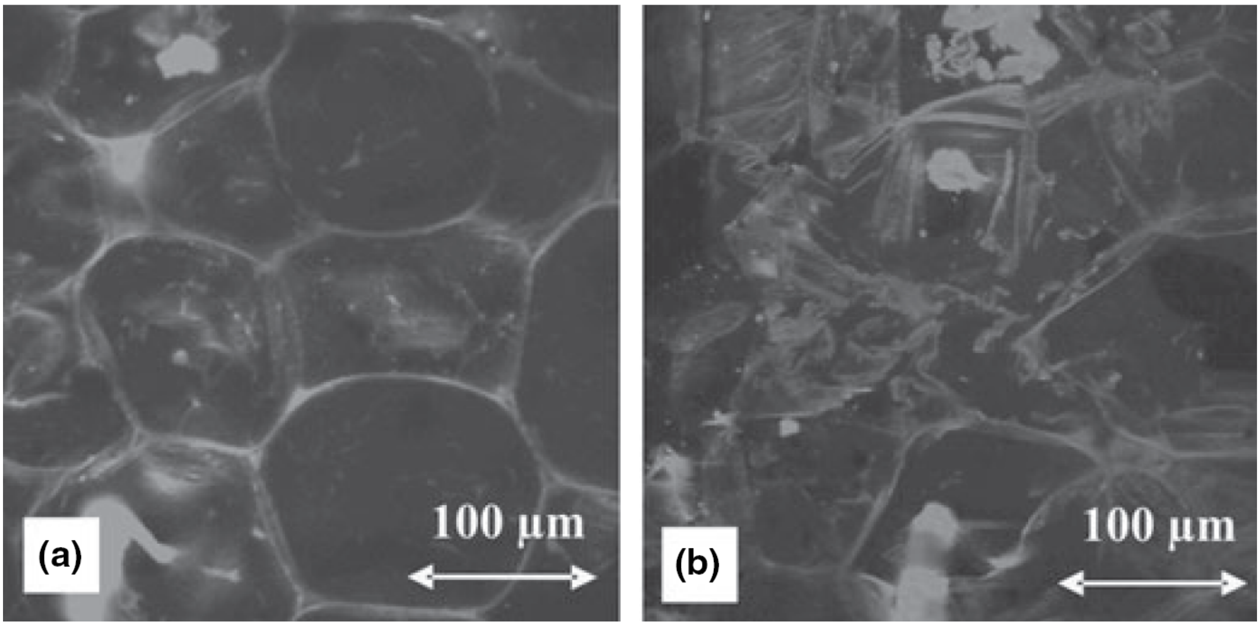

Fig. 3. Confocal microscopic observations in fluorescent mode of a) potato surface and b) French fries surface after frying at 170°C for 6 min [*cell wall observation using natural fluorescence of cellulose (Goulas, Moya & Schmuck, 1990) when exitated in UV (351nm)*].

Concerning the period of oil uptake, the first experimental observations of Ufheil & Esher (1996) on potato slices showed that oil absorption occurred during cooling. They carried out successive frying experiments adding dyed oil to the oil bath at different moments of frying and quantified the amount of dyed oil in the fried potato chips with an extraction-refractometric method. They found that even if the dyed oil is added only during the final period of frying, the proportion of dyed oil in the fried product is still very high. Therefore, oil does not enter the potato chips during frying, but rather is absorbed from the superficial oil layer when the product is removed from the fryer due to depressurisation of the product during water condensation. However, some authors think that a little oil absorption takes place during frying. Bouchon *et al.* (2003) noted that a small amount of oil they called "structural oil" (in opposition to the oil adhering to the surface or oil sucked up during cooling), could be absorbed during frying. This small amount could depend on the drying rate and the total duration of frying. Moreover, Saguy and Pinthus (1995) suggested that when the dehydration rate decreases during frying, the rate of oil absorption increases due to the reduction in the internal steam pressure of pores. Mehta & Swinburn (2001) added that there was a little fat uptake while the product is immersed in hot fat and steam is still escaping. In agreement with their observations, figure 4 shows the experimental results of oil distribution during frying and cooling of a potato slice. During frying, a small amount of oil is absorbed by the potato, while during cooling, the internal oil content increases at a fast rate for the first minute of cooling while surface oil decreases until an equilibrium is reached after 4 min of cooling.

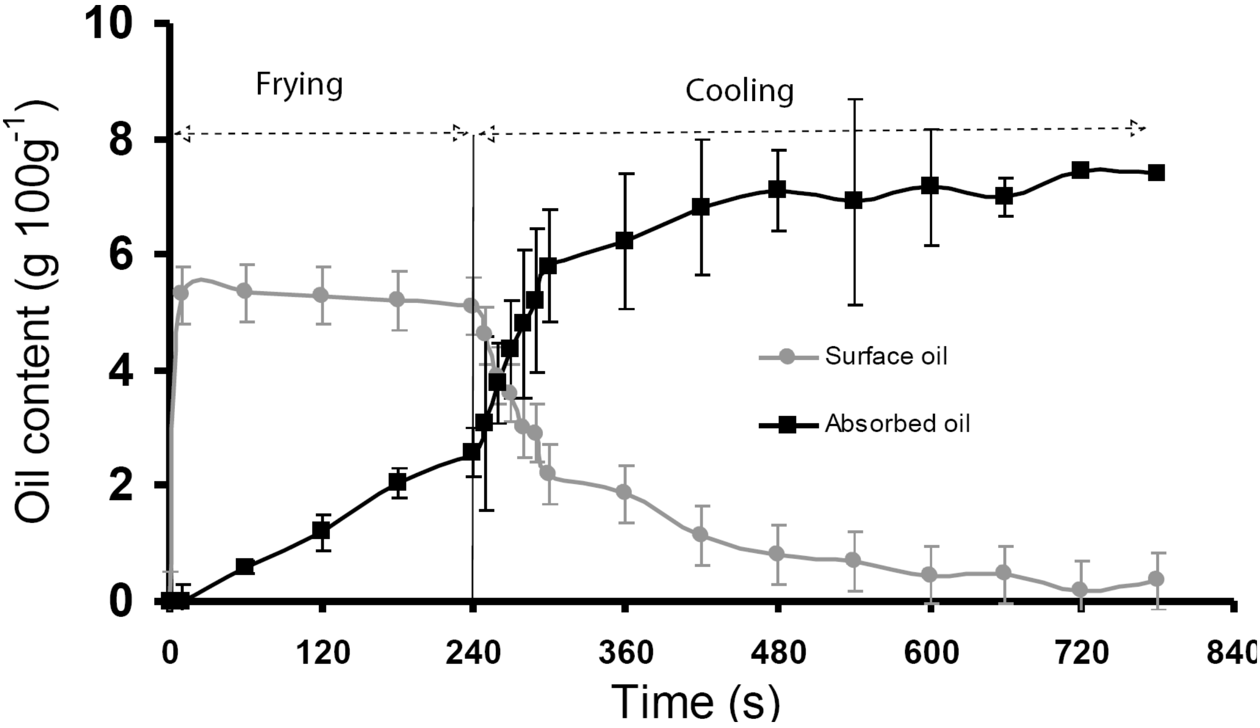

Fig. 4. Oil content absorbed or remained on the surface of French fries during frying (170°C) and cooling (20°C) [*Surface and absorbed oil content discrimination using Moreira method (Moreira, Sun & Chen, 1997) with petroleum ether]*.

To conclude, according to experimental observations, oil is absorbed mainly during cooling and this phenomenon seems to be closely linked to the hydrothermal history of the product.

4. Mechanism of oil absorption

Oil uptake is a complex mechanism, which is not still clearly understood. The initial product structure, the various interchanges between the product and the heating medium, and the variations of product and oil properties are the factors which complicate this phenomenon.

4.1 Water escape and oil uptake

Most of the authors agree that during frying heat and mass transfer are controlled by heat transfer at the surface of the product. The rate of vaporisation is proportional to the temperature difference between the oil and the boiling point of water (Vitrac *et al.*, 2002). Numerous works propose a simple description based on a convective mass transfer approach that is too simple. Farkas, Singh & Rumsey (1996) were the first scientist to propose a physical description of frying. They stated that this process should be described as a complex Stephan problem because of the coupled heat and mass transfer resulting in the displacement of a moving vaporization front that separates two dynamic regions: a dehydrated crust and a humid core. Since the crust presents low thermal conductivity, it affects heat and mass transfer and is partly responsible for the decrease in the dehydration rate.

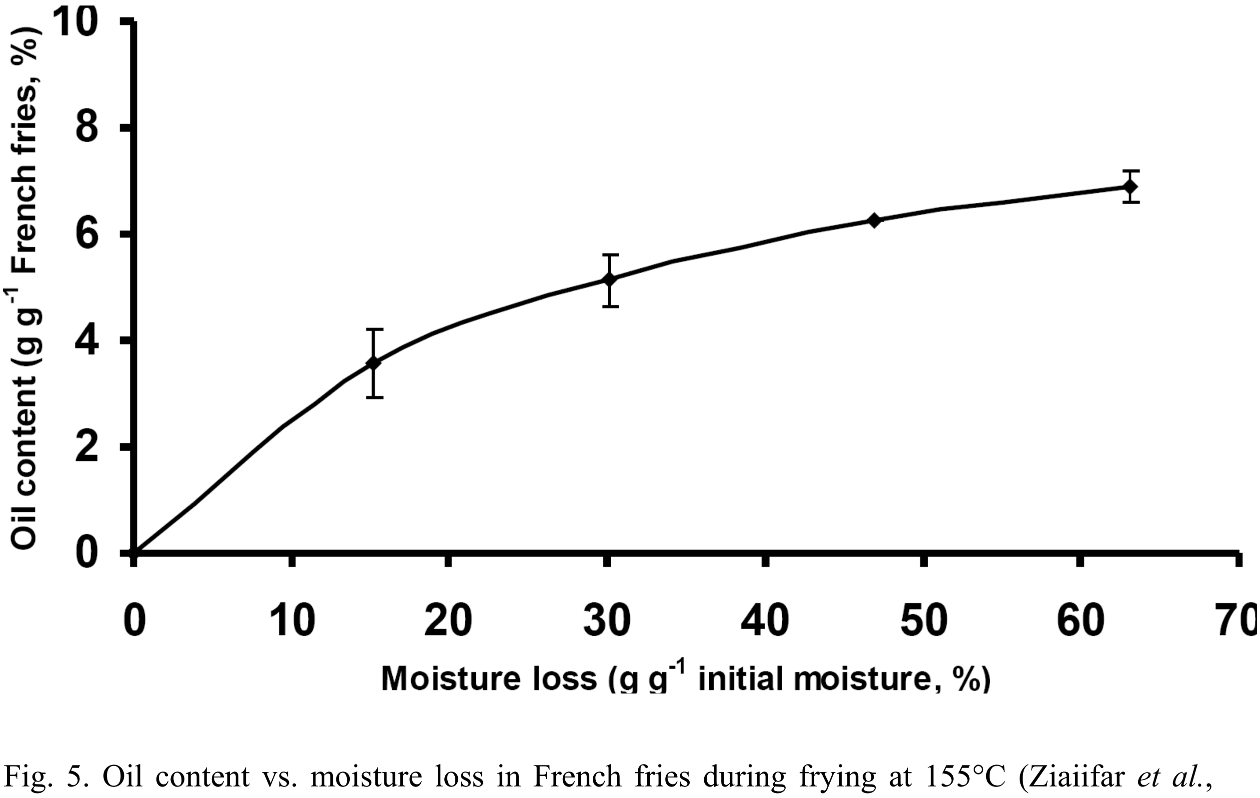

Fig. 5. Oil content vs. moisture loss in French fries during frying at 155°C (Ziaiifar *et al.*, paper in preparation).

In general, we can say that the more the water is removed from the surface, the more the oil is absorbed. In figure 5 the relationship between oil content and moisture loss is plotted. Indeed, when mass transfers in deep-fat frying are studied, the escape of water is usually linked to oil absorption. Indeed, Gamble *et al.* (1987) found that moisture loss and oil uptake were interrelated and were both linear functions of the square root of frying time. They made the hypothesis that the oil entering the slice would lie in the voids left by the escaping water. Hence, in addition to quantitative aspects, water loss can become an explanatory variable for transformation and especially oil uptake because water escape is at the origin of very diverse material phenomena such as the creation of cavities (Vitrac, 2000). Indeed, as dehydration occurs at a temperature above 100°C, water steam finds selective weaknesses in the cellular adhesion that leads to the formation of capillary pathways increasing surface porosity. Furthermore, some of this vapour may be trapped within the pores due to restrictive intercellular diffusion and expand, becoming superheated, distorting the pore walls and contributing to product porosity. Accordingly, some studies have examined the increase of porosity during frying and correlated it to the amount of oil uptake (Pinthus *et al.*, 1995; Moreira *et al.*, 1997). Characterisation of the product microstructure thus appears to be a determining factor in the description of transfers at the macroscopic scale such as oil uptake.

4.2 Capillary pressure and oil uptake

Moreira *et al.* (1999) introduced a physical relation between oil absorption and porosity stating that the mechanism of oil uptake may be caused by capillary forces. Indeed, when a fluid displacement such as oil absorption occurs in micro canals like crust pores, surface phenomena such as viscosity or capillary forces become very important. Capillarity is the ability of a narrow pore to draw a liquid upwards. It occurs when the adhesive intermolecular forces between a liquid and a solid are stronger than the cohesive intermolecular forces in the liquid. This effect causes a concave meniscus to form where the liquid is in contact with the vertical surface. This phenomenon causes a difference of pressure between the two sides of the curbed interface expressed by the Laplace law (figure 6):

$$P_1 - P_2 = \frac{2\gamma \cos\theta}{r} \qquad (1)$$

where P_i is the pressure at the point i (Pa), γ the surface tension of the oil ($N\cdot m^{-1}$), θ the wetting angle between the oil and the solid (rad), and r the pore radius (m).

In addition, $P_2 - P_3 = -\rho g h$ according to the hydrostatic pressure difference (figure 6) where ρ is the oil density ($Kg\cdot m^{-3}$), g the acceleration gravity ($m\cdot s^{-2}$), and h the height of the capillary motion (m).

Therefore, the pressure difference ΔP at the two points 1 and 3 of the pore is:

$$\Delta P = P_1 - P_3 = \frac{2\gamma \cos\theta}{r} - \rho g h \qquad (2)$$

Therefore, oil absorption is dependant on pore radius. Small pores cause higher capillary pressures and then a higher oil content (Moreira *et al.*, 1997). In addition, the lower the contact angle between oil and the product surface, the higher the adhesion forces and the higher the oil uptake. Finally, the higher the surface tension of the liquid, the higher the oil uptake. Moreira and Barrufet (1998) stated that γ decreases with increasing temperature, resulting in a capillary pressure reduction. This fact contributes to limiting oil uptake during frying.

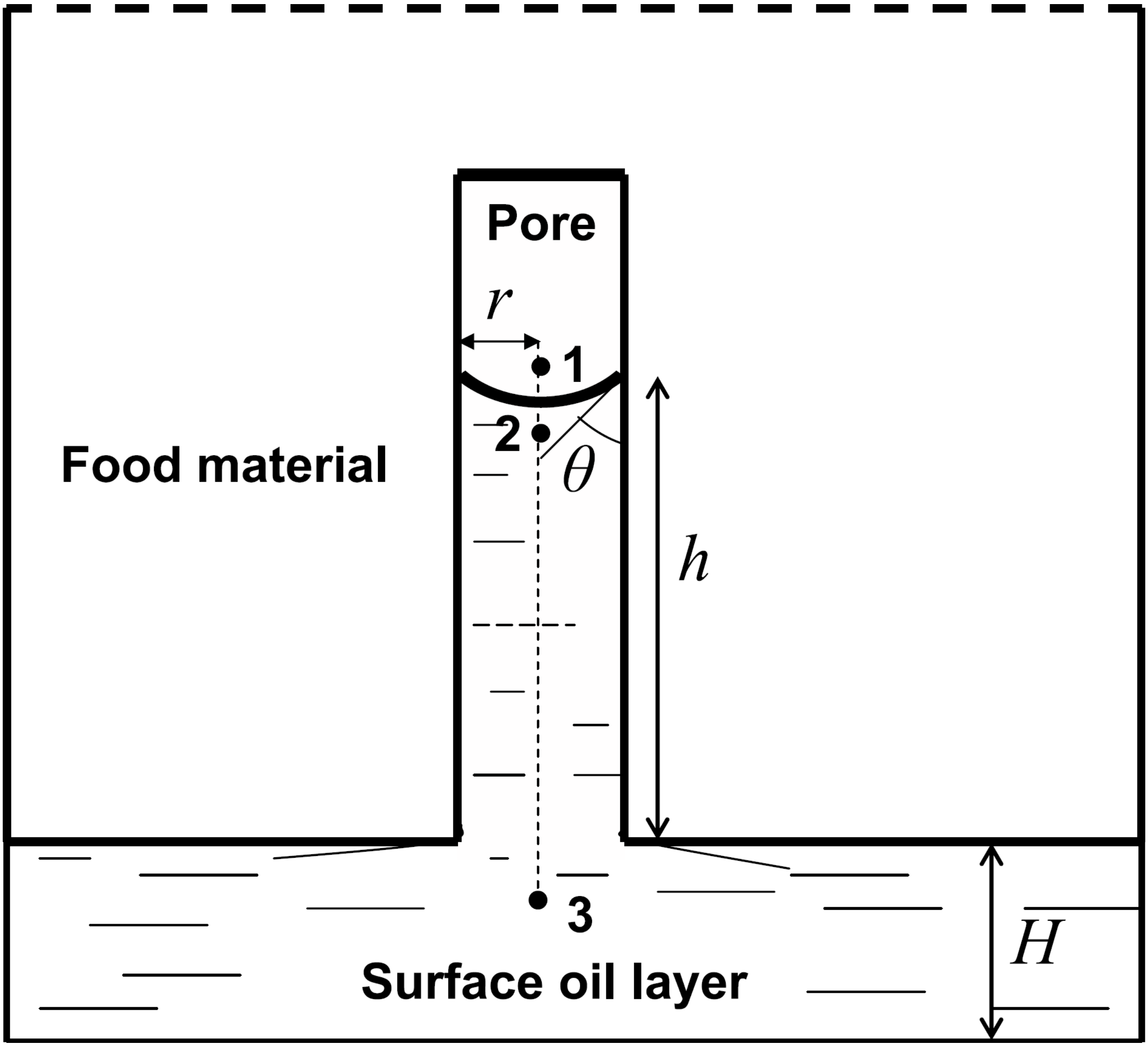

Fig. 6. Diagram of oil flowing into a pore.

The main difficulty with capillarity motion determination at the end of frying is the determination of pore radii that are non-homogenous in shape. Furthermore, pores can be filled with liquid, water vapour or air depending on the conditions at the end of frying. Thus, the wetting property of oil toward the solid matrix is non homogenous and difficult to determine in such complex and multiple fluid phases systems. Moreover, capillary motion equations are mostly used in their static form resulting in the expression of the equilibrium positions of fluids. This simplification comes from the fact that other forces, such as vacuum effect and the weight of absorbed oil, are involved in oil absorption (see equation 5).

4.3 Vapour condensation and vacuum effect

During frying, intense drying occurs at a temperature superior to the temperature of water ebullition. The solid matrix of the food is an obstacle to water bubble growth that leads to a pressure gradient in the food. Overpressure was evaluated in experimental work by Vitrac (2000). He measured an inner overpressure of 45kPa during the frying of an alginate gel containing 10% starch. This overpressure depends on the initial structure of the material. Indeed, the more resistant the structure toward fluid dilatation, the higher the pressure inside the material. However, some structures are not resistant enough to pressure and can break, allowing liquid water to escape. This phenomenon of water loss in both steam and liquid forms was observed during deep-fat frying of apple slices (Vitrac *et al.*, 2003).

Consequently, during frying, when the product still presents high free water content susceptible to evaporate, the escape of water and the associated overpressure in the material is an obstacle to oil absorption. In opposition, when the product is removed from the fryer, core temperature decreases, steam condenses and the pressure in the product abruptly decreases. As a consequence, the important difference between inner and outer pressures creates a "vacuum effect" and results in the penetration of the surface oil into the product (Gamble & Rice, 1987; Moreira & Barrufet, 1996). Moreover, measurements by Vitrac (2000) of depression in a food model gel were evaluated at 35 kPa a few seconds after the product had been removed from the oil bath. He therefore stated that this vacuum is the most important force acting on oil uptake in the porous media.

4.4 Adherence and drainage of oil

Oil absorption involves a balance between adhesion forces (capillary and water condensation) and drainage of oil during the cooling period (Ufheil & Escher, 1996). In the case of frying, adherence, which is an important factor in oil uptake, is the ability of the oil to stick to the outer surface of the product. Drainage is the removal of surface oil due to gravity forces.

Theoretically, when a solid is removed from a bath of wetting liquid, it drags out a liquid film the thickness (*H)* of which (figure 6) has been by Landau-Levich-Derjaguin relation (Krozel *et al.*, 2000):

$$H = 0.94 \frac{(\mu U)^{2/3}}{\gamma^{1/6} (\rho g)^{1/2}} \qquad (3)$$

where μ is the oil viscosity (Pa·s), γ its surface tension (N·m^{-1}), U the speed of removal (m· s^{-1}), ρ the oil density (Kg·m^{-3}), and g the gravity acceleration (m· s^{-2}).

Experimental data from Quéré about fibre coating showed that the film formed in the case of slow withdrawals from pure viscous liquids such as oils fits the Landau law. At high withdrawal velocities, the thickness decreases with the velocity because the solid can only drag the viscous boundary layer. Furthermore, the presence of surface-active compounds may cause a thickening of the film (Quéré & De Ryck, 1998).

4.5 Conclusion: toward a possible modelling of oil uptake?

In conclusion, oil uptake is a complex mechanism resulting of the hydrothermal history of the product. Water removal mode and intensity, depending on raw product properties and process parameters are determining factors for oil absorption since they control the amount of oil absorption (linked to the importance and the geometry of the porous structure), the location (in the voids made by water) and time depending on water steam pressure in the pores. Nevertheless, oil absorption also depends on the oil properties involved in the adhesion and drainage forces and the conditions of product removal from the oil bath. For this reason it has been observed that oil content is high even for very short frying times (i.e. when loss is low) (Ufheil & Escher, 1996; Aguilera & Gloria, 1997; Bouchon *et al.*, 2003). Reciprocally, it can be imagined that for longer frying times, when product porosity becomes high, that the oil layer dragged out will become the limiting factor for oil uptake. In conclusion, the representation of oil uptake exclusively via water removal is not sufficient to explain the phenomenon and further experimental studies are needed to evaluate limiting factors during the cooling period.

Recent efforts have been made in order to model oil uptake according to the highlighted mechanisms. However, models have difficulty providing realistic results because authors do not agree about the most important forces for oil uptake. Moreira and Barrufet (1996) developed a model of oil uptake during cooling in tortilla chips and deduced that the major cause for oil flowing into the product was capillary pressure. Indeed, they showed experimentally that oil uptake takes place during the first 20s of cooling, that is to say when the temperature of tortilla chips is well above the condensation temperature of 100°C, suggesting that the effect of water vapour condensation is negligible. The models considered a uniform micro porous media whose medium radius was dependant on the initial water content. During cooling, the void spaces constituted during frying were filled by oil and gas and oil was considered as a non-infinite medium surrounding the product (i.e. oil layer Thus, during cooling, oil flowing into the pores was controlled by the pore radius and oil interfacial tension (increasing with the decrease of the product temperature). The limitation of the height of oil came from the void available in the product defined by the initial water content and oil depletion at the surface. Later, Ni & Datta (1999) developed a multiphase porous media model to predict energy transfer, water loss and oil uptake during frying. They assumed that the fried product was a multiphase porous media and stated that the gas phase (vapour and air) transport takes place by convective and diffusive flows while the liquid phase (water and oil) transport happens by convective and capillary flows. They stated that oil absorption happens during the frying period as water moves out and they did not take into account the effect of cooling time on oil absorption. They explained that the rate of oil uptake was more important in the early stage of frying when there is a larger difference between surrounding and absorbed oil concentrations. In conclusion, this model is interesting but not really close to the physical reality and is dependant on many input parameters (diffusivity values, porosity…). More recently, Bouchon & Pyle (2005) have provided a very interesting model considering heat and mass transfer firstly during frying (i.e. water loss) and then during cooling (i.e. oil uptake). Therefore, the final state of the product at the end of frying was realistically the initial state during cooling. To model oil uptake, they have chosen the Washburn equation derived from the Hagen-Poiseuille equation to get the laminar oil flow Q through a uniform pore (perfect cylinder of radius r):

$$Q = \frac{dh}{dt} \cdot \pi \cdot r^2 = \frac{\pi \cdot r^4}{8 \cdot \mu \cdot h} \cdot \Delta P \qquad (4)$$

where ΔP is the pressure difference between the pore surface (P_1) and the deepest pore point (P_3) pressures (Pa) as represented in figure 6, r the pore radius (m), μ the oil viscosity (Pa·s), and h the height of the oil in the pore (m). However, contrary to Moreira, they consider that the pressure difference ΔP is due not only to capillary pressure but mainly to the water pressure in the pore during cooling as assumed by Vitrac (2000). Therefore, Bouchon et *al.* have modified the Washburn equation, enriching the total driving pressure with 2 terms in addition to capillary pressure:

$$\frac{dh}{dt} = \frac{r^2}{8 \cdot \mu \cdot h} \cdot (P_{atm} - P_v + [(2\gamma \cos\theta)/r] \pm \rho g h \cos\alpha) \qquad (5)$$

The first term $P_{atm} - P_v$ represents the unbalanced atmospheric pressure due to the change of the water vapour pressure P_v during cooling. The second term $\pm \rho g h \cos\alpha$ is related to the influence of gravity upon oil drainage in different product positions during cooling where α is the angle between the normal axis of the product surface and the vertical axis. Therefore, oil ascension in the pores will go on as long as the pressure difference is positive.

It would be very interesting to modify the Bouchon equation as a quick numerical analysis shows that:

- This equation is undefined for h=0 (initial time of oil uptake).
- The second term added (i.e. gravity drainage) is negligible as compared to the others. It is probably better to keep only the two other terms to simplify.
- h will grow indefinitely, even beyond product boundaries. To address this problem, the variable P_v should reflect the fact that the reachable volume in the pore decreases as oil fills the pore volume.

In addition, it would be interesting to question the oil film thickness formed when the product is removed from the fryer which is considered infinite in the Bouchon study. Indeed, this thickness depends on oil viscosity and thus oil temperature and the conditions of product removal.

In conclusion all models previously developed present interesting points but have difficulty representing the global reality of oil uptake. Furthermore, most of the models consider r and l as simple mean values while they are probably highly dispersed variables. For instance, in equation (5), an uncertainty of only 10% in r leads to more than 46% change in Q. Furthermore, combining 10% uncertainties on r and l can change Q by more than 62%. Another highly sensitive parameter is μ, the oil viscosity which is known to vary significantly with temperature. For instance, a 69% decrease was found when oil temperature varied from 100 to 200°C (Tseng *et al.* 1996). In opposition to r and l, it is much easier to get a precise characterization of the relationship between oil viscosity and temperature since the Arrhenius equation is commonly used for this purpose.

5. Important factors in oil uptake

5.1 Product properties affecting oil uptake

5.1.1 Size, shape and surface of product

As oil uptake is a surface phenomenon, the specific dimensions of a food will determine the oil that can be taken up. Results show that oil absorption increases significantly when product thickness is reduced and product surface is increased (Guillaumin, 1983). For instance, French fries absorb less oil than chips because of a smaller surface/volume ratio, as shown in table 1

(Paul & Mittal, 1997). A linear relationship has been set between surface area and oil content (Gamble & Rice, 1988). Since most of the fat penetrates the food through the pores in the crust, the structural properties of the outer layer of the food are important. Indeed, cells broken during cutting are a privileged location for oil absorption (Saguy & Pinthus, 1995). Using good quality blades for cutting can therefore reduce the surface roughness of the product and thus the surface area, resulting in lower oil uptake.

Food	**Water content [g/100g wet basis]**	**Oil content [g/100g wet basis]**	**Water content [g/g non fat dry matter]**	**Oil content [g/g non fat dry matter]**
Raw products				
Plantain, Rojas, 2006	60	0.1	1.53	0.005
Potato, Talburt, 1987	80	0.1	4	0.005
Eggplant, Kalogeropoulos, 2006	95	0.1	19.38	0.005
Cassava, Vitrac, 2000	60	0.1	1.50	0.005
Tortilla dough, Moreira, 1999	47	1.5	0.88	0.03
Fried products				
Plantain cylinders, Rojas, 2006	32	7	0.80	0.15
French fries, Talburt, 1987	44	13	1.05	0.30
Potato chips, Talburt, 1987	2	40	0.03	0.69
Eggplant cubes, Kalogeropoulos, 2006	50	40	3.85	2.71
Cassava chips, Vitrac, 2000	2	25	0.05	0.35
Tortilla chips, Moreira, 1999	2	25	0.025	0.35

Table 1. Water and fat content in various raw and deep-fried products

5.1.2 Composition of product and its density

As shown in table 1, from a humid raw product, deep-fat frying provides more or less high fat content products depending on their initial composition and thickness. Indeed, initial solid content in the product is a factor that influences oil uptake during frying because of the relationship between water loss and oil uptake (Kozempel et al., 1991; Pinthus & Saguy, 1994; Moreira et al., 1997; Krokida et al., 2001; Yamsaengsung & Moreira, 2002). Indeed, for a final fried product that exhibits an intermediary water content (i.e. thick product) such as plantain cylinders, French fries or eggplant cubes, the higher the initial water content, the higher the final oil uptake (table 1). Similarly, a higher potato density (1103 kg.m-3 compared to 1093 kg.m-3) can reduce oil content by about 10% (Ufheil & Escher, 1996) because of the relationship between a product's density and its initial water content (Paul & Mittal, 1997). Table 1 data also shows that the important moisture loss occuring during frying of thin products (i.e. chips) leads to considerable fat uptake because of the extensive void volumes created by the water escape (Gamble et al., 1987). Finally, the ability of a raw material to present or develop high porosity during frying, mainly due to a high level of initial water content or extensive water loss, will control oil uptake. However, the typical behaviour of eggplant during frying has to be noticed. Indeed, even if the residual water content is still quite high after frying (only 50% of initial water is removed), oil uptake is as high as in totally dehydrated products like chips. This phenomenon can be explained by the fact that eggplant is an aqueous non starchy product whose structure is very weak and spongy (Kalogeropoulos et al., 2006).

5.2 Frying Oils properties and oil uptake

5.2.1 Oil type

The effect of oil type is very different depending on the author. Kita & Lisinska (2005) wrote that fat absorption is higher when the amount of unsaturated fatty acid increases in oil. On the other hand, Vitrac showed that oil uptake is weaker with an unsaturated oil such as cotton oil than with palm oil because of the former's weak viscosity during cooling and its ability to drain easily (Vitrac, 2000). These contradictions could be explained by the fact that oil viscosity is very influential in the oil absorption mechanism but is involved both in adhesion and draining dynamics (equations 3 and 4). Moreover, the frying oil may contain a portion of fat that solidifies upon cooling and be harder to drain or shake from the food as well as being less likely to penetrate deeply into crust pores. Fat content can be considered to be a sum of both fat penetration into the crust and fat crystallization on the surface.

The higher the oil viscosity, the slower the oil migration (equation 4). Initial oil viscosity depends on the oil type but also on the temperature and oil quality. As shown in figure 7, oil viscosity decreases with a decreasing temperature following the Arrhenius equation. Oil initial superficial tension is also an important factor to consider in the capillary action leading to oil uptake (equation 1). An increase in interfacial tension leads to an increase in oil uptake. Therefore, the addition of surfactants (surface-active agents or wetting agents) such as Tween80 (Polysorbate) and Span80 (Sorbitan monooleate) in the frying oil could change surface properties and modify oil content in the final product (Pinthus & Saguy, 1994). However, these products are not widely approved for food use.

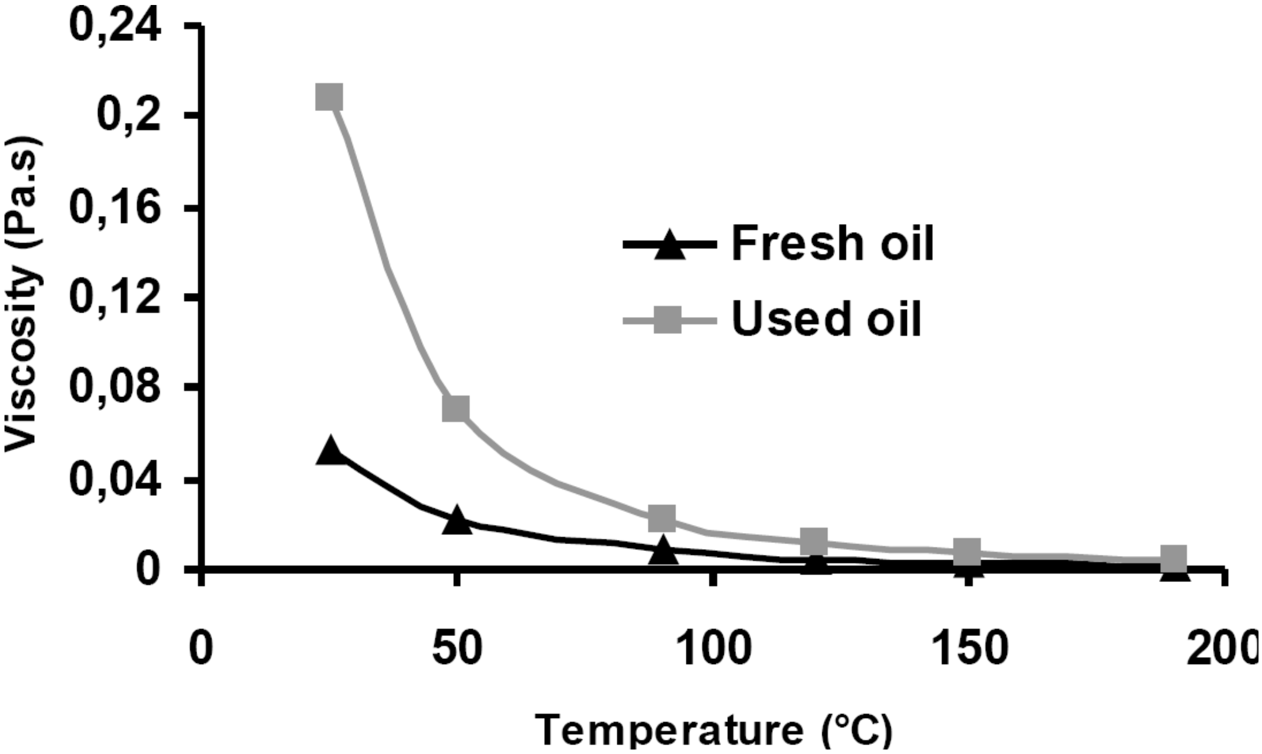

Fig. 7. Viscosity changes in fresh and used soybean oils (Tseng et al., 1996).

5.2.2 Oil aging

The result of oil aging is an increase in viscosity due to polymer formation (figure 7) and the decrease of contact angle due to the formation of polar compounds. The increase of viscosity could contribute to an increase in oil quantity on the food surface according to equation 3 while the decrease of contact angle could increase the wetting properties of the oil, both resulting in higher oil content. For this reason Tseng *et al.* (1996) argued that surface oil on tortilla chips increased with oil degradation (figure 3). Still, some studies prove that the total final oil content of tortilla chips is not significantly affected by the oil quality between the first and 30th frying operations (Mehta & Swinburn, 2001). Nevertheless, this chemical evolution that can have adverse effects on oil quantity and quality can be slowed down by the addition of natural or synthetic antioxidants (Che Man & Jaswir, 2000; Houhoula *et al.*, 2004). In conclusion, oil aging plays a role in oil uptake, but its effect is less than expected (Mellema, 2003).

5.3 Process factors

A wide spectrum of process factors including the conditions of preprocessing, frying, and post frying has been reported to affect oil absorption in fried foods as presented in figure 8. Some of these process steps and conditions have been patented as means of decreasing oil uptake and are shown in table 2.

5.3.1 Preprocessing factors affecting oil uptake

The most popular processes applied before frying of products at the industrial scale are blanching, air drying, osmotic dehydration, steam baking and surface treatment (coatings).

Blanching is a process of food preparation where the food substance is plunged into boiling water or steam used for enzyme and micro-organism inactivation. The effect of this pre frying process on final oil uptake is quite ambiguous because of the different conditions applied. Some authors (Rimac-Brncic *et al.*, 2004) state that blanching before frying decreases the dry mass content of the product because of the migration of water soluble components from the product to the blanching water. As a result, this phenomenon increases water content and thus final oil content (Alvarez *et al.*, 2000; Pedreschi *et al.*, 2005). On the other hand, as highlighted in other studies, surface starch gelatinization that occurs during blanching could form a firm thin layer that protects the food from oil absorption (Califano & Calvelo, 1987).

In addition, blanching can activate pectin-esterase enzymes that can make surface cell walls collapse, causing a decrease in the porosity and oil content of the product (Aguilera-Carbo *et al.*, 1999).

Drying prior to frying is another way used to create a firm and dried surface material matrix around the product. This technic decreases the total water content of the product and limits oil absorption (Lamberg *et al.*, 1990; Moreira *et al.*, 1999; Vitrac, 2000). Moreover, the shrinkage that occurs during drying reduces total surface area and consequently diminishes mass transfer. Finally, this preprocess is interesting in two ways: it decreases oil uptake while improving organoleptic properties of the product by increasing its crispness (Debnath *et al.*, 2003).

Similarly to convective drying, osmotic dehydration, described as a partial dehydration by immersion of the raw product in a concentrated solution which is usually sugared or salted, decreases oil content by decreasing the initial water content of the product. Krokida *et al.* (2001) showed that French fries soaked in a sugar solution (40% w/w) exhibited 60% reduction in fat content, while soaking in NaCl (20% w/w) and maltodextrine solutions (20% w/w) for the same treatment times resulted in lower reductions in oil content of 35% and 15%, respectively.

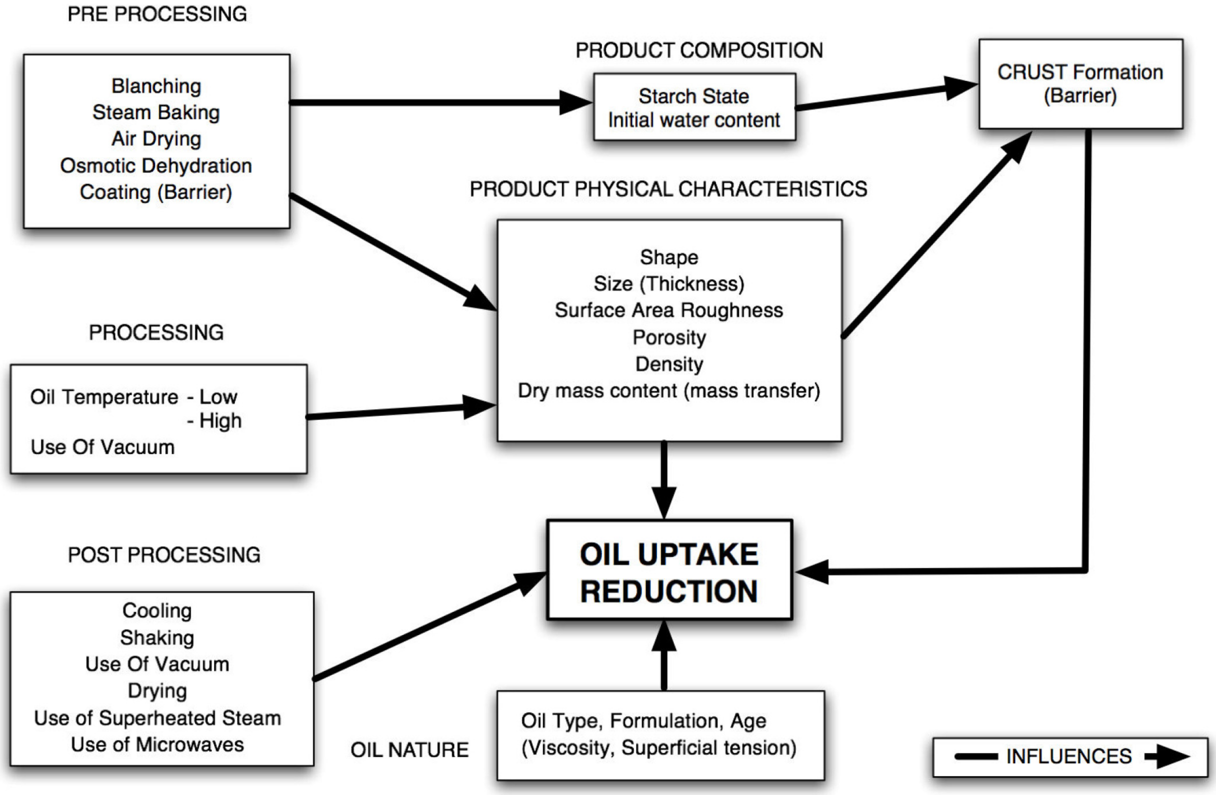

Figure 8: Important factors involved in the frying operation affecting oil uptake.

Finally, steam baking, like blanching and air drying, can be used to form a tight barrier at the outer surface of the product because of severe starch gelatinization. This outer layer presents strong resistance to oil entrance into the product. Hence, the final internal oil content is lower in the steam-baked products and most of the oil remains at the surface of the product (Rajkumar et al., 2003).

Coating is another pre-frying technique that consists in dipping a raw product in a coating suspension for a short time immediately before it is fried. This surface treatment reduces surface porosity and also builds a barrier against oil absorption. Indeed, coating decreases not only fat uptake but also water loss during frying. The most important properties for good hydrocolloids are their film formation ability, heat stability, fat and water transfer properties, organoleptic and nutritional qualities. Some of the most commonly used and efficient hydrocolloids are cellulose derivatives such as hydroxypropyl cellulose (HPC), methyl cellulose (MC), and hydroxypropylmethyl cellulose (HPMC) (Albert & Mittal, 2002). Coatings appear to be an effective method for reducing oil uptake: some experimental studies have demonstrated that oil uptake could be reduced by 40% in French fries using cellulose coatings before frying although their water content was higher et al., 2002; Mellema, 2003).

Process Step	Principle	Method	Patents
Pre frying	**Product shape** *Favouring oil drainage*	Cone product shape	Minoru, 2004
	Air drying *Limitation of frying time*	Drying of potato slice at 150 to 250°C from 1 to 3min before frying	Geun, 2003
	Coating *Physical barrier against oil uptake*	Addition of film forming agent in batters surrounding the product : - Starch, gelatine - Carboxymethylcellulose - Protein	- Olson, 1995 - Mottur, 1985 - Kelleher, 2005 - Feeyney, 1993
Frying	**Temperature optimization** *Control of food transformations*	Beginning of frying at low temperature : Starch caramelisation: physical barrier against oil uptake End of frying at high temperature	Jonhson, 2005
	Vacuum frying: *Limitation of oil suction*	Frying under a pressure of -100 to -750mmHg at 70 to 140°C.	Tadao, 1988 Ryuichi, 1993
Post frying	**Air drying:** *Limitation of frying time and de-oiling effect*	Partial frying followed by air drying to decrease water content of the product	Lee, 1988
	Superheated steam drying *Limitation of frying time and de-oiling effect*	Partial frying at low temperature (100-130°C) Drying with superheated steam	Mazaki, 2006
	Microwave cooking *Limitation of frying time*	Partial frying at low temperature followed by microwave cooking	Chujin, 2001

Table 2: Patented works to limit oil uptake during the frying operation.

5.3.2 Frying factors

The quality of products is the result of the deep-fat frying conditions which determine oil distribution in the product, its structure and its flavor properties (Rajkumar *et al.*, 2003).

5.3.2.1 Oil temperature and frying time couple

The frying temperature depends on the type of product, its size and components, and varies from 120°C to 190°C. High oil temperatures (160–190°C) enable rapid heat transfer, rapid browning and short frying time. For this reason, putting too large an amount of cold food into hot fat is detrimental to product quality and process efficiency because it causes a dramatic decrease in fat temperature and longer cooking time. At the industrial scale, a good food to oil ratio is generally 1/6 (Mehta & Swinburn, 2001).

An increase in oil temperature triggers an increase in dehydration and coupled reactions speeds. Therefore, high temperatures limit frying time. However, for the same residual content, the effect of frying temperature is marginal and some authors even argue that temperatures between 140°C and 190°C have no influence on oil absorption (Gamble & Rice 1987; Moreira et al., 1997). However, the incitation of limiting oil temperature in order to limit its degradation motivated the study of frying temperatures below 140°C. These works showed that a temperature such as 120°C resulted in longer frying time and higher oil uptake for the same residual water content (Talburt, 1987; Pedreschi & Moyano, 2005; Moyano & Pedreschi, 2006; Rojas et al., 2006). This phenomenon can be explained by the higher oil uptake during frying caused by the longer frying time and the weaker opposite water flows or by the development of different crust structures (i.e. a different porosity more likely to enhance oil uptake). Indeed, during frying at a very low oil temperature, such as 120°C, crusts exhibit a low level of firmness that could let the oil penetrate easily into the product (Blumenthal & Stier, 1991).

5.3.2.2 Vacuum frying

Vacuum frying makes it possible to fry at a lower oxygen concentration and at a lower frying temperature because of the decrease in the water boiling point. This process can therefore preserve natural colors and flavors of a product and limit oil degradation. In addition, Garayo & Moreira (2002) have demonstrated that the final oil content is lower for chips fried under vacuum pressure than for those fried at atmospheric pressure while enabling the same dehydration time. More recently Liu-Ping & Mujumdar (2005) have stated that the rate of moisture loss and oil uptake increases while the degree of vacuum increases for carrot chips and Tan & Mittal (2006) have found that oil uptake is higher in donuts fried under vacuum than those fried at atmospheric pressure for the same final moisture content. In conclusion, vacuum frying has been poorly studied and its effect on oil uptake is not clearly recognized.

5.3.3 Post-frying conditions

When the product is removed from the frying medium, its temperature immediately starts to decrease. Below 100°C, water vapour condensates and the internal pressure drops, resulting in the creation of a positive pressure vacuum favouring oil uptake. The most important factors affecting oil absorption during post frying are the cooling conditions. Indeed, temperature influences oil viscosity and interfacial tension that are involved in oil uptake phenomena. Matz (1993) stated that if the product is removed from the fryer while its temperature is still increasing, oil uptake will be lower (Matz, 1993). The hydrodynamics of cooling are also important: vigorously shaking the basket of fried products immediately after removal from the fryer can drain the surface oil if it is still liquid and has not yet been sucked into the pores. The oil which would be able to penetrate the pores is thus limited (Thanatuksorn *et al.*, 2005).

Along with this previous effect, post-fry drying (convective air drying or superheated steam) can reduce final oil content by reducing the contact time between the product and the oil (Topin & Tadrist, 1997; Li *et al.*, 1999). For instance, Myers & Loewe (1990) has reported a technique of premature removal of the product from the fryer at high moisture content followed by subsequent drying using superheated steam. This combination resulted in a 30% reduction in oil uptake. However, the main inconvenience of superheated steam drying is the high temperatures reached which may cause damage to heat sensitive products. Finally, microwave finishing after frying can also be an alternative process enabling a low oil content (Blau *et al.*, 1965). However, this technique is hard to introduce at the industrial scale because of difficulties in controlling the drying process.

6. Conclusion

Many process factors influence oil uptake. For this reason many pre- or post-frying steps have been optimized to lower final oil uptake. However, many steps such as coating or soaking bring exogenous materials that can transform at high temperature and affect final product quality. Moreover, the influence of the frying process parameters (including cooling), such as temperature or pressure, still presents contradictions in the literature. Higher reduction of oil in fried products could thus be expected with further understanding of oil uptake mechanisms in relation to process parameters. More precisely, works on pressure could be interesting to prevent the oil from entering into the product. In addition, as oil adhering to the surface of the product is also a determining factor in oil content, ways of reducing the adhering forces during the cooling period by shaking and drainage should be found. Finally, additional work could be carried out to optimize the physical properties of the frying oils.

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In the second part of chapter 2, we tried to review the literature attempts in modeling of frying process. Many efforts were done in order to optimize and control the frying process. The development and solving of a predictive mathematical model for the heat and mass transport in frying are necessary to improve the process.

The main objective was to compare the different models for heat and mass transfer during frying process. The mechanisms of the moisture departure from the product and the ways of oil uptake into the product from the frying oil were discussed. This review showed a need to obtain the meaningful data in order to model the frying process. This was why the experimental works in the last part of the thesis were performed in order to obtain to the precise thermal conductivity not in the whole product but in the crust and core regions separately.

Part 2: Modeling of heat and mass transfer during deep-fat frying: a review

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Abstract

Models to describe frying process are needed for engineering design and optimization. Many studies in the recent years have followed the goal of developing the mathematical models describing heat, moisture and fat transfers during deep-fat frying process. In this paper, the different models which are developed in the literature for frying process are reviewed. The models were classified by several criteria. The important characteristics of product such as formation of two different sections (crust and core) and the conditions of process such as considering the cooling period after frying are largely discussed and their effect in model development were analyzed. The mechanisms and important factors in heat and mass transfers during frying process are also discussed.

Key words: Frying, modeling, heat and mass transfer, oil absorption

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1. Introduction

Deep-fat frying is a very old process that has grown exponentially over the last years. The theoretical aspects of the frying process are highly complex and difficult to understand. According to Farkas *et al.* (1996), immersion frying period may be broken into four stages: initial-heating, surface boiling, falling rate, and bubble end point. Initial-heating is described as the initial immersion of a raw material into hot oil and is characterized by the absence of water vaporization. During this stage heat is transferred from the oil to the food via free convection and through the food via conduction. Stage two, surface boiling, is characterized by the sudden loss of free moisture at the surface, increased surface heat transfer, and beginning of crust formation. The falling rate stage is characterized by continued thickening of the crust region, decreased heat transfer, and a steady decrease in vapor mass transfer from the material. Bubble end point is characterized by the apparent stop of moisture loss from the food during frying.

A good understanding of existing frying theory (mechanisms of heat and mass transfer) together with new experimental data will enable further advances in the description of the frying phenomena. The process optimization can be achieved by the mathematical model which is based on fundamental physical principles. Development of mathematical models to describe frying process has been a topic of research in several products (French fries, tortilla chips, etc.) for two decades. Models are necessary to enable scientific process design and minimization of energy cost subject to quality controls. Many assumptions are made in order to generate most models, resulting in over simplifications of the process which are necessary due to the complexity of the various phenomena involved. The objective of this research was to review the presented models related to heat transfer, moisture loss and more particularly oil absorption during deep-fat frying process. Table 1 illustrates some of the numerous efforts in order to modelling the frying process.

Table 1. Verify of modelling approaches to model frying found in literature (Diff. = Diffusion, Cap. = Capillary)

Authors	**Product**	**Product phase**		**Period of oil uptake**		**Nature**		**Transfer**		
		Single	**Double**	**Frying**	**Cooling**	**Empirical**	**Mechanistic**	**Heat**	**Mass Transfer**	
									Moisture	**Oil**
Mittelman et al. (1984)	French fries	*				*		*	*	
Asheknazi et al. (1984)	Food	*				*		*	Controlled by heat transfer	
Rice & Gamble (1989)	Potato slice	*					*		Diff.	
Keller & Escher (1989)	French fries	*					*	*	Controlled by heat transfer	
Kozempel et al. (1991)	French fries	*		*		*	*		Diff.	Zero order kinetics
Atteba & Mittal (1994)	Meat	*		*			*	Diff.	Diff.	Diff.
Moreira et al. (1994)	Tortilla chips	*		*			*	Diff.	Diff.	first order exponential
Baumann & Escher (1995)	Potato cube	*		*		*			Exponential model	multiple linear regression
Farkas et al. (1995)	French fries		*	*			*	Diff.	Diff & Press. driven	
Dincer & Yildiz (1996)	Sausage	*		*			*	Diff.	Diff.	
Courtois et al. (1998)	Banana		3 phases				*	*	Compartmental	
Farid & Chen (1998)	Potato chip		*		*		*	Diff	Diff	
Mittal & Ateba (1999)	Meat	*		*			*	Diff	Diff	Diff.(absorb.), Cap.(desorp.)

Table 1 continued

Authors	**Product**	**Product phase**		**Period of oil uptake**		**Nature**		**Transfer**		
		Single	Double	Frying	Cooling	Empirical	Mechanistic	Heat	Mass Transfer	
									Moisture	Oil
Ni & Datta (1999)	Potato slab		*	*			*	*	Diff. (vapor), cap. (liquid)	Diff
William & Mittal (1999)	Coated food		*					Diff.	Diff.	Diff.
Costa & Oliviera (1999)	French fries		*				*	Diff.	Diff. & compartmental	
Krokida et al. (2000)	Potato slabs	*				*		*	First order kinetic	First order kinetic
Gupta et al. (2000)	French fries	*		*			*		first order kinetic	First order kinetic
Southern et al. (2000)	Potato crisp		*				*	Diff.		
Vitrac et al. (2002)	Chips	*					*	Diff.	Cap.	
Yamsaengsung & Moreira (2002)	Tortilla chips		*		*	*		Diff.	Diff.	Cap. only
Moyano & Berna (2002)	French fries	*					*		Diff.(variable)	
Bouchon & Pyle (2005)	Potato		*		*		*	Diff.	*	Wasburn equation
Fasano & Mancini (2006)	Potato slice		4 phases	*			*	Diff.	Diff.	
Halder & Datta (2007)	Potato slab		*	*	*		*	*	Pressure driven & Cap.	Cap. Diff.
Yildiz et al. (2007)	French fries	*					*	Diff.	Diff.	

2. Classification of frying models

The presented models in literatures can be grouped by different criteria such as:

2.1. Model types classified by the different zones in product

Several changes occur in a food material during frying, the important one being the development of a crust at the surface of the food. In the two-zone models, the heat and mass transfer is separately studied in both zones (crust and core) which are different in thermo-physical characteristics.

2.1.1. Single zone model

Most of the models have considered the product as a single zone in which the present of crust is neglected. Single zone model explains the equations of heat and mass transfer for the whole product with no taking into account the difference between core and crust. Dincer & Yildiz (1996) developed a single zone model by solving the diffusion equation for both heat and mass transfer. Table 1 shows that this type of model was the rule until Farkas *et al.* (1996) developed a model by considering the two parts of product.

2.1.2. Double zone model

Some products such as potato are subjected to frying form two distinguished regions: core and crust. During frying, the surface of potato heats up to the saturation temperature and water starts to evaporate. As frying progresses, the evaporation front (crust/core interface) moves towards the centre of product, and crust is formed. Each region is in a dynamic state during frying, the crust becoming thicker and the core decreasing in thickness (Farkas *et al.*, 1996). Within each region simultaneous heat and mass transfer occurs leading to thermal and moisture gradients. The regions are defined by a change in physical and thermal properties, or a change in the mass or energy flux of the system. Farid & Chen (1998) have used the physical properties of fresh potato and the completely fried chips to represent the properties of the core and crust regions respectively. Figure 1 shows the heat and mass transfer during frying process. The moving front is the limit between the core and crust and is going towards the core as frying progresses.

Farkas *et al*. (1996) stated that frying can be considered as a complex form of the Stefan class of problem. The generalized Stefan heat transfer problem is characterized by the presence of a moving interface which divides two regions of distinct physical and thermal properties. They assumed that the crust region, which increases in thickness during frying, is defined by two criteria: temperature of the crust region is higher than the boiling point of the liquid present in the food material, and the concentration of liquid water is negligible. They used a two-zone model, crust and core, providing different sets of equations for the two regions, separated by a moving boundary. They applied unsteady heat transfer conduction equation to describe heat transfer in both separated regions. They considered water diffusion flow within the core region and they believed that water vapor movement was pressure-driven. The final set of equations consisted of four nonlinear partial differential equations, which were solved using finite differences. The results were compared with experimental data; and they obtained a reasonable prediction for temperature profiles, water content and thickness of the crust region. Halder *et al*. (2007), reviewing the hypothesis of Farkas *et al*. (1996), stated that the neglecting vapor flux in the core and liquid flux in the crust reduced mathematical complications but sacrificed important physics.

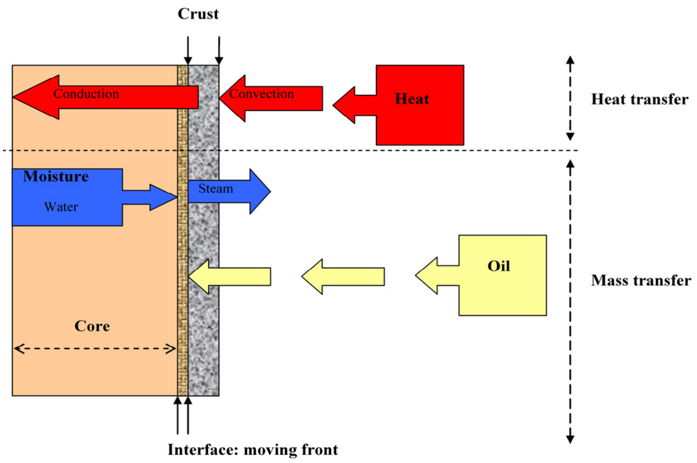


Figure 1. Transfer phenomena (heat and mass transfer) during frying of French fries.

2.2. Model types by period of oil absorption

Many studies related to oil absorption have been carried out in recent years; however, most of them have been limited to observations on the frying period rather than the whole frying process which includes a certain cooling time removing the food from oil. The single-period model does not take into account the cooling period while the two-period model is based on both periods of frying process i.e. frying and cooling.

2.2.1. Single period model for oil absorption

Some authors assumed that the oil absorption takes place when the product is still in frying oil, and concluded that oil transfer is independent from water vapor transfer. Such assumption simplifies the analysis of heat and mass transfer during frying. Baumann *et al*. (1995) stated that oil uptake starts as soon as the surface of the potato slices is dried slightly and its rate remains constant over the frying time. Later, Ni & Datta (1999) developed a multiphase porous medium model to simulate the frying of potato slices. In their model, oil absorption was considered to happen during frying and the effect of cooling period was neglected.

2.2.2. Double period model for oil absorption

This model includes both frying and cooling periods as oil absorption period. Cooling starts immediately after frying, when the product is removed from the fryer. As cooling begins, the temperature within the slab starts to decrease; however evaporation of water does not stop instantaneously. During the first few seconds, some heat can still be provided from the crust region, as it cools down, to the evaporation front (ref). As a consequence, the temperature of the crust/core interface remains at the evaporation temperature. This is particularly important for the model for oil absorption during cooling because during early stage of cooling the crust region is filled with water vapor exerting an external pressure opposing suction of the oil. In addition, results obtained by Aguilera & Gloria-Hernandez (2000) support the hypothesis that a certain finite cooling period is necessary before oil suction occurs.

Sun and Moreira (1994) observed that almost 64% of the total oil content is absorbed by tortilla chips during the cooling (post-frying) process. According by, Duran *et al*. (2007) stated that oil could penetrate in chip microstructure either during frying or during cooling. They added that potato chips absorbed during frying at 180°C nearly 38% of the total oil content, and almost 62% of the total oil content remained at the chip surface without penetrating into the microstructure. This situation reverses during the cooling stage and 65%

of the total oil content was absorbed by potato chips and only 35% remained at the chip surface. Their results are in agreement with the results of several authors (Ufheil & Escher, 1996; Bouchon *et al*., 2003).

2.3. Model types by nature

Empirical models which may provide a simpler prediction of frying process don't have theoretical basis while mechanistic models are based on the theoretical aspects of process (mechanisms) which could response to the complexity of process to some extent. These models normally include heat transfer, moisture loss and oil uptake behaviours regarding to the physical, structural and thermal properties of food materials.

2.3.1. Empirical model

Empirical model (empirical curve) fits experimental data, and is the simplest description of frying. It is suited for a particular food material and specific processing conditions and cannot be applied for a general class of food or process. The prediction of this kind of models would be greatly affected if there is any change in physical property or environmental conditions (Halder *et al*, 2007). Mittelman *et al*. (1984) had proposed a semi-empirical relationship for heat and mass transfer during frying. They stated that the rate of frying (expressed by rate of water evaporation) was proportional to the square root of frying time and the difference between the oil temperature and the boiling temperature of water. Later, Krokida *et al*. (2000) developed an empirical first order kinetic model for moisture content and oil absorption of potato strips during frying and fitted to experimental data.

2.3.2. Mechanistic model

Mathematical modelling can provide a level of understanding that complements experimentation in ways that are impossible to achieve with experiments alone (Halder *et al.,* 2007). Mechanistic model which is more comprehensive model includes systems of simultaneous equations with all the thermodynamically interactive fluxes. The complexity of the frying process induces the development of mechanistic models to describe this process.

Keller and Escher (1986) proposed a mathematical model for the frying of potato sticks with the addition of a term for the sensible heat required to heat the dry crust region from the boiling point of water to the oil temperature. In modelling of tortilla chips, Moreira *et al.* (1996) used the finite difference method to solve the equations of heat and mass transfer. This method is commonly used in the modelling process; it can be a powerful tool in predicting certain parameters involved in the frying process. The mechanistic models were largely discussed in next section.

3. Transfer phenomena: heat transfer and mass transfer

The coupled heat and mass transfer problem makes frying one of the most difficult unit operations to understand. During the frying process, mass transfer includes the moisture loss and oil uptake. The water vapour flows through the material and oil is transferred into the material. Datta (2007) stated that the complexities of frying process are due to several factors such as changes in mechanisms of transport and changes in product properties. In addition, fried foods are listed in porous media resulting in more complex heat and mass transfer. Figure 1 shows the mechanisms of heat transfer, moisture loss and oil absorption during the frying process.

3.1. Heat transfer during frying process

The frying process is controlled by the heat transfer between the frying oil and the product. Heat is transferred through two resistances in series: the oil film and the crust. The major characteristic of deep frying is to transfer heat into the food at a very high speed using a large amount of hot oil. This rapid heat transfer is due to higher heat capacity of oil when compared with other heating elements such as hot air and superheated vapour. As can be seen in figure 1, the heat transfer takes place in two difference modes during the process of deep-fat frying: convection and conduction. At first, heat is transferred from the frying oil to the surface of the product by convection. Then, it is transferred from the surface to the inner part of product by conduction. The heat conduction depends to the changes in thermal properties of the food such as specific heat, thermal conductivity and density. The rate of heat convection is related to water evaporation state that changes during frying. During early stage of frying, the water evaporation increases and bubbles form and move forcefully throughout the oil resulting in oil agitation. Oil agitation causes a turbulence movement which increases the heat convection resulting in more heat transfer. In the last stage of frying where the moisture content decreases, the heat convection diminishes. Fellows (1996) stated that the generated bubbles due to high water loss can play an inverse role to heat transfer. He added that the large bubbles that don't flow away from the product surface rapidly create a resistance to heat transfer.

3.1.1. Mechanisms of heat transfer

a. Heat convention

Convective heat transfer coefficient measures the rate of heat transfer from the oil to the food product. Califano and Calvelo (1991) measured the convective heat transfer coefficient as a function of oil temperature using the lumped method (Holmann, 1981) by heating a copper cylinder in a bath of oil. They found that the convective heat transfer coefficient (*h* value) varies from 150 to 165 W/m^2K for a temperature ranged between 50 to 100°C. Tseng *et al.* (1996) found that *h* value decreases as oil quality decreases. Miller and Singh (1992) concluded that the convective heat transfer coefficient of soybean oil at 180°C was higher (282 W/m^2K) for fresh oil than for used oil (261 W/m^2K). Similar results were obtained by Moreira *et al.* (1992) for soybean oil at 190°C (285 for fresh and 273 W/m^2K for used oil). Sahin *et al.* (1999a) determined heat transfer coefficient during frying at temperatures between 150 and 190°C. They found the heat transfer coefficient during frying of the one-dimensional potato slice to be between 90 and 200 W/m^2K within the temperature range studied. They also reported that heat transfer coefficient increased, while moisture content and thermal conductivity decreased with the increasing oil temperature. Costa *et al.* (1999) investigated the effect of water loss rate on heat transfer coefficient during frying at 140 and 180°C using the lumped system approach and the surface temperature data. They found that heat transfer coefficient reached a maximum value of 443 W/m^2K at 140°C and 650 W/m^2K at 180°C for French fries. They reported that although the bubble movement during frying increase the rate of heat transfer, maximum levels of water loss rates may hinder the heat transfer. Hubbard and Farkas (1999) determined the heat transfer coefficient during frying of infinite potato cylinders at 180°C from the time–temperature data acquired at the product surface and reported that heat transfer coefficient increased from its initial value of 300 W/m^{2}K to 1100 W/m^{2}K during the frying process. Figure 2 shows our experimental study of the variation of h value during frying of French fries.

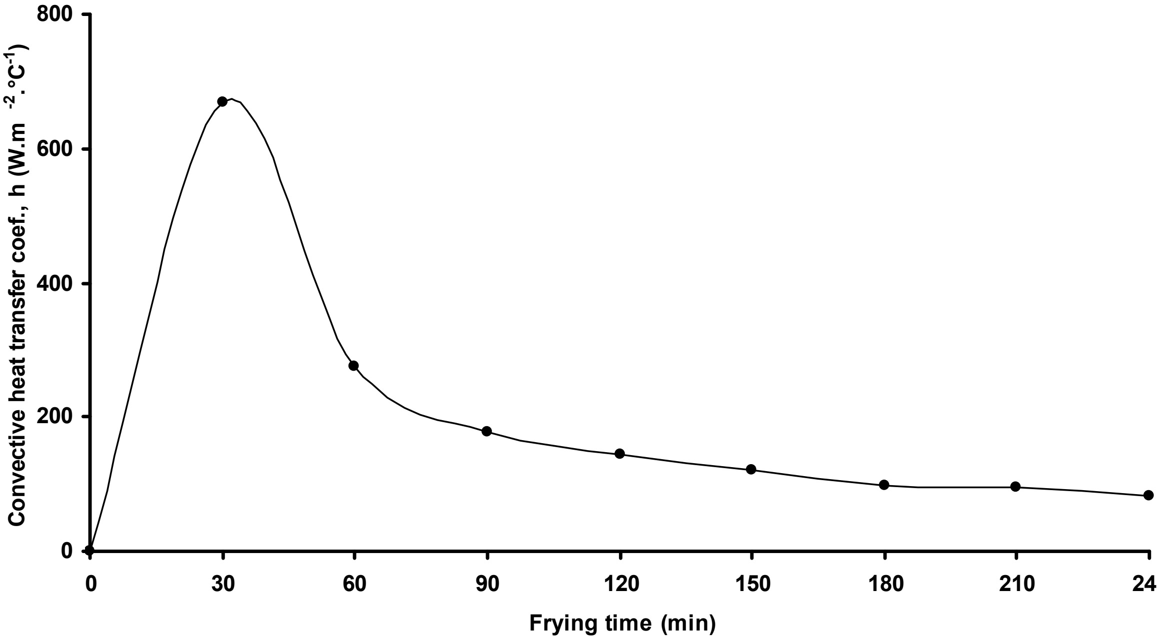


Figure 2. The variation of convective heat transfer coefficient during frying of French fries at 185°C (calculated by the method used by Hubbard and Farkas, 1999)

Many authors take into account that the convective heat transfer coefficient is constant during frying (Ni and Datta, 1999; Yamsaengsung and Moreira, 2002) and some assumed two different values: turbulence convective heat transfer due to bubbling and another one in the absence of bubbling (Hubbart and Farkas, 1998; Costa *et al.*, 1999; Budzaki & Seruga, 2005). Use of a constant convective heat and mass transfer coefficient through the process is not reasonable since Hubbard and Farkas (1999) showed through experiments that both heat and mass transfer coefficients vary significantly during different stages of frying and need to include in modelling.

The convective heat transfer coefficients were up to two times higher than those obtained in the absence of vapour bubbling and vary with the water loss rate, showing a maximum when the maximum moisture loss rate is reached. The *h* values reported in the literature in the absence of bubbling vary between 250 and 300 W/m^{2}K in the temperature range of 170-

190°C (Miller *et al*., 1994; Tseng *et al*., 1996), while for surface boiling conditions at the initial heating period it is reported to be 800-1000 W/m^{2}K (Fellows 1996). Costa *et al*. (1999) stated that the heat transfer coefficient may be position dependent. The heat transfer coefficient is higher at the top surface than bottom surface because at the top surface the agitation causes more heat transfer while at bottom surface the big water vapor bubbles may lead to an increased resistance to heat transfer.

Farid & Chen (1998) stated that the sensible heating is always very small when compared to the latent heat of vaporization. They assumed that the heat transferred from the oil to the surface of the product is totally utilized for evaporating the water from the thin layer of the potato. Hubart and Farkas (2000) used a sample heat balance to predict the *h* value during frying. In agreement with Farid & Chen (1998), they supposed that the output of energy from the material is much greater than the accumulation of energy in the porous matrix or crust region so that they have neglected the heat needed for heating the crust when it is compared with the heat needed for water evaporation. They measured the product surface temperature and water loss rate. They showed that in the beginning of frying the *h* value started at 300, reached to a maximum value of 1100 and then diminished below 200. Later, in disagreement with their work, Costa *et al.* (1999) have stated that some of the heat transferred from the oil is used for heating the potato crust; this heat is not negligible. Yildiz *et al*. (2007) found that heat transfer coefficient decreases with increasing oil temperature during frying of French fries. Their finding contradicts those of Costa *et al*. (1999), Sahin *et al*. (1999b), and Budzaki and Seruga (2005b), who reported an increase in convective heat transfer coefficient with an increase in frying oil temperature. They explained that the higher temperature results in quicker water loss. The greater the water loss rate, the larger the amount extracted from the incoming energy. This will reduce the amount of energy available for internal energy increase and as a result the effective heat transfer coefficient will decrease.

a. *Heat conduction*

Unsteady heat conduction in an infinite slab geometry is defined as:

Eq. 1 $$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

where, *T is the temperature (°C), t is time (s),* α *is the heat diffusivity (*$m^2\ s^{-1}$*), x is the position (m).*

Donsi *et al.* (1996) measured the thermal conductivity of potato having difference moisture content by establishing heat flow between the hot water and the cooper plug with insulation of apparatus. They showed that the conductivity of potato decreases with the decrease in water content and stated that this parameter also is related to structure modifications occurring during processes. They added that among the physical properties relevant to process modelling, thermal conductivity is one of the most critical, being the controlling parameter of almost all thermal processes. Later, Sahin *et al*. (1999b) stated that the heat conductivity decreases with the increase in frying temperature. They added that the decrease in thermal conductivity with increasing time and/or temperature is due to the evaporation and oil uptake. Since thermal conductivity depends on composition as thermal conductivity of oil is lower than that of water. These studies didn't account for the effect of starch gelatinization on heat conductivity. Recently, Ziaiifar *et al*. (2008) studied the heat conductivity in crusts and core (Figure 3). As can be seen, in the core region the heat conductivity increases and reaches a maximum then it decreases. The important factors in this variation are the starch gelatinization and water loss which happen in this region. In crust, top and bottom, heat conductivity decreases; this shows that the structure of formed crust changes during frying. The top crust has smaller heat conductivity when compared with bottom one.

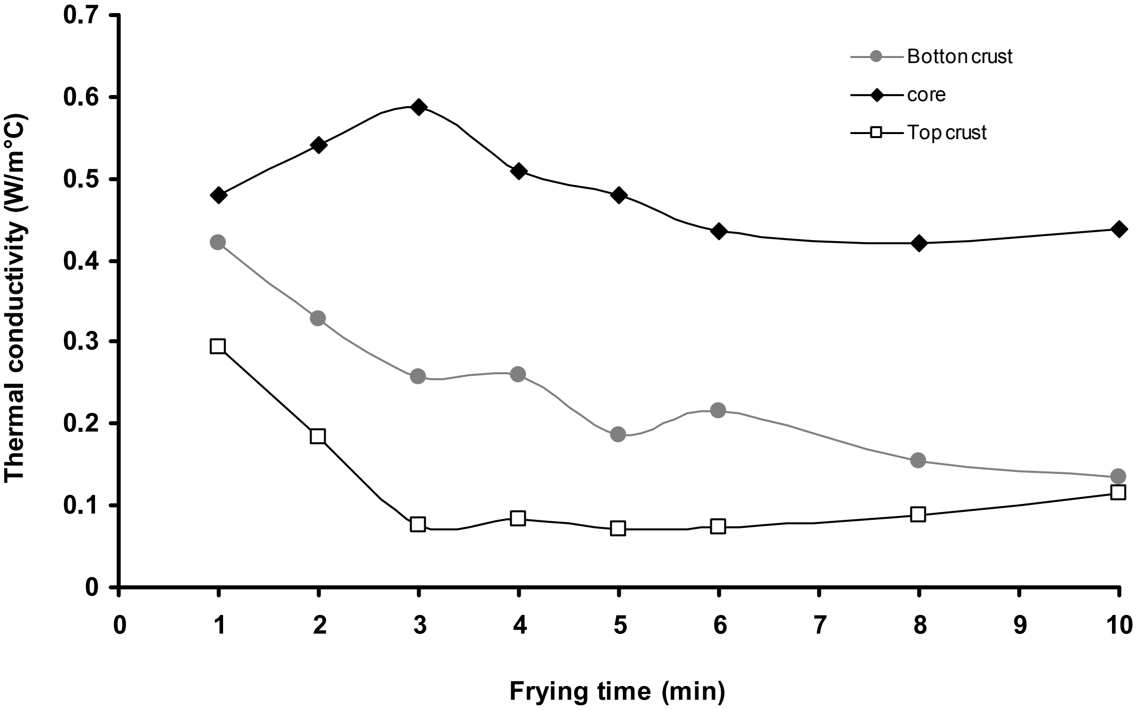


Figure 3. The heat conductivity at difference positions of French fries (Ziaiifar et al., 2008, see chapter 3 part 3)

3.1.2. Modeling of heat transfer

When the food temperature reaches to water evaporation temperature, the heat is transferred by convection from the oil to the surface of food, then by conduction in the crust and finally is totally used to evaporate the water as:

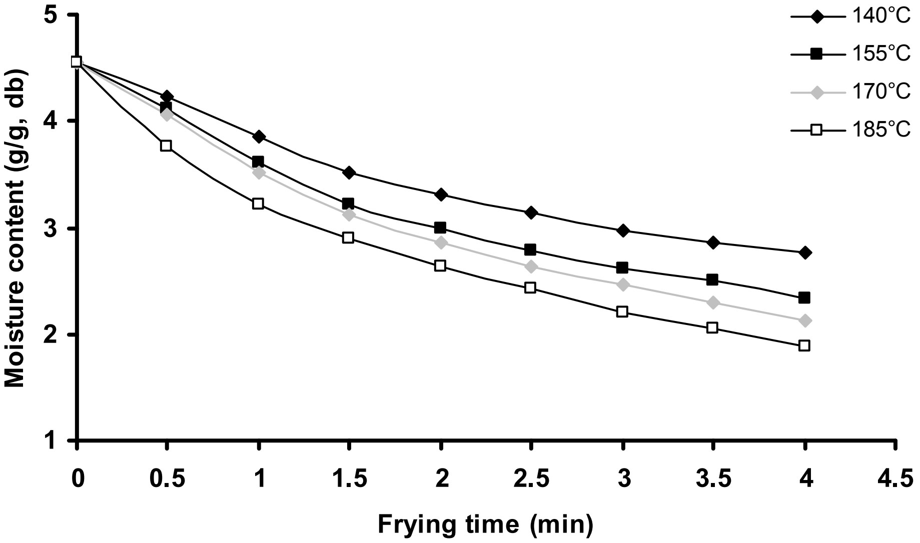
Eq. 2
$$q = h_c A(T_\infty - T_L) = \frac{k_{Cr}}{(L-\delta)} A(T_L - T_{evap}) = \lambda \rho_w \varepsilon A \frac{d(L-\delta)}{dt}$$

where, h_c *convective heat transfer coefficient (*$Wm^{-2}K^{-1}$*), A surface area (*m^2*), q heat flow (*$j\ s^{-1}$*),* T_∞ *oil temperature (°C),* T_L *Product surface temperature (°C),* k_{Cr} *crust thermal conductivity (*$Wm^{-1}K^{-1}$*), L distance between center and surface (m),* δ *distance between crust and center (m),* T_{evap} *water evaporation temperature (°C),* λ *latent heat of vaporization (*$Jkg^{-1}C^{-1}$*),* ρ_w *water density (*kgm^{-3}*),* ε *water volume fraction and* $(L-\delta)$ is crust thickness.

3.2. Moisture transfer

Moisture loss is an important factor in frying process. It plays determining role not only in heat transfer, as explained before, but also in oil uptake due to its ability to create pores. During frying, a partial vapour pressure difference between product and frying oil causes the water to evaporate. Costa *et al*. (1999) showed that the water loss rate is very slow at the beginning of frying and then abruptly increases up to a maximum after which water losses decrease approximately exponentially with time. The variation of French fries moisture content during frying at difference temperatures is shown in figure 4. As can be seen, the rate of moisture loss changes during frying. The higher frying temperature, the higher the rate of moisture loss.

a.



b.

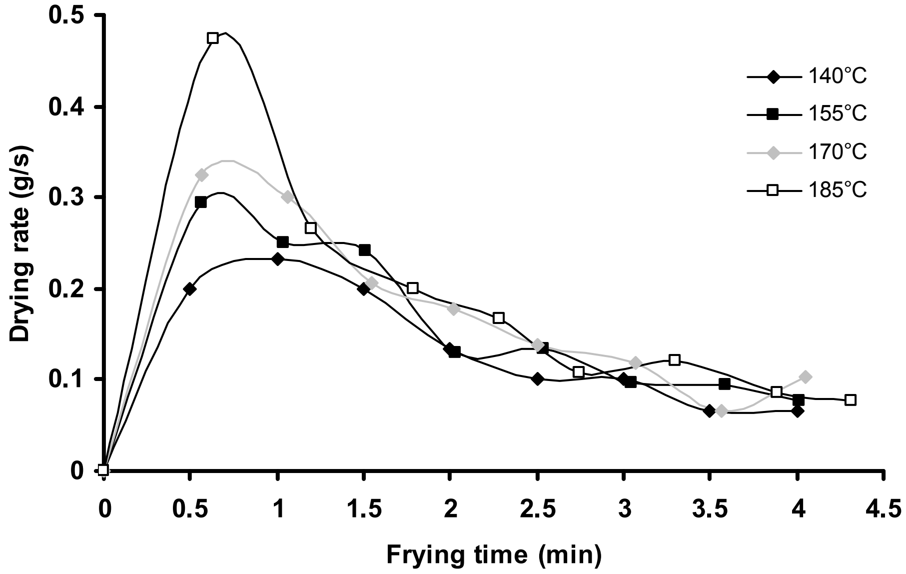


Figure 4. Moisture loss (a) and drying rate (b) during frying of French fries at different temperatures (Ziaiifar, non published work)

<u>3.2.1. Mechanisms of moisture transfer</u>

In a food with large water content, capillary diffusion of liquid water can be the dominant mechanism for moisture transport and molecular diffusion of vapour may not contribute as much. In such a situation, it may be possible to ignore molecular diffusion. Ni & Datta (1999) stated that if significant internal evaporation and pressure generation take place, pressure driven or Darcy flow becomes quite important. For the weak evaporation situation, vapour transport is ignored and liquid transport by capillarity can be formulated in two equivalent ways, one using capillary pressure and the other using a capillary diffusivity (Datta 2007). Due to the differences in capillary attraction, flow of liquid can occur from locations in the solid having more water to locations having less water, i.e., from higher concentration to lower concentration of water. This is referred to as unsaturated flow and is extremely important in food processing. Gravity is ignored in most studies. Perhaps this can be justified from the fact that the food material is generally unsaturated where capillary forces are much stronger than gravity (Datta, 2007).

a. Diffusion gradient

With different approaches, the Fick's law of diffusion has been extensively used to describe the water loss kinetics during frying (William & Mittal, 1999; Rice & Gamble, 1989; Kozempel *et al*., 1991; Ateba & Mittal, 1994; Yildiz & Dincer, 1995; Chen & Moreira, 1997; Mittal & Zhang, 2000). It provides a simplified picture of the water loss during frying. Diffusion theory assumes that liquid moves through a solid body as a result of a concentration gradient. Due to the surrounding heating media, in fact, water evaporates from the food surface, creating a diffusion gradient, driving inner water toward the surface, and thus producing a continuous steam flow.

Fick's second law is used in non-steady or continually changing state diffusion, i.e., when the liquid concentration within the diffusion volume changes with respect to time in infinite slab.

Eq. 3
$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

where, *C is the concentration (mol* m^{-3}*), t is time (s), D is the diffusion coefficient (*$m^2\ s^{-1}$*), x is the position (m)*

Gamble *et al*. (1987) proposed that once the unbound water is lost from the product, the surface becomes dry, providing a diffusion gradient, and the inner moisture is converted to steam, causing a pressure gradient. The steam is then lost discontinuously through minor or major sites through the surface of the product. This hypothesis may be correct once no changes were in the product during process. During the frying of starch base product such as potato, the starch gelatinization occurs. This phenomenon results in structural changes within product which can affect the way of moisture transfer. Starch gelatinization starts when the potato temperature reaches 58-65°C so that it absorbs water and generates an osmotic pressure that makes the potato cells become round and separate from one another (Aguilera *et al*., 2001). These simple diffusion-based frying models provide very limited understanding of the frying process as complex processes.

b. Capillary flow

Capillary theory assumes that flow of liquid through the capillaries is caused by solid-liquid molecular attraction. Water movement may be described by a capillary flow, which is more influenced by the solid –liquid interaction such as interfacial surface tension, pore size, etc.

Eq. 4 $$P_{cap} = \frac{2\gamma \cos\theta}{r}$$

Where, P_{cap} *is capillary pressure (Pa),* γ *interfacial tension (Nm^{-1}),* θ *wetting angle between the oil and the solid, r pore radius (m)*

c. Darcy's Law (pressure driven flow)

Like Fourier's law of heat conduction and Fick's law of mass diffusion, Darcy's law is an empirical relationship (Datta 2007). Darcy's Law indicates that the transport phenomena is controlled by the structure of the dried layer of food (permeability, porosity, tortusity, etc), as well as the physical properties of the fluid. Farid (2002) have stated that the use of Fick's Law of diffusion to describe the diffusion of vapour during drying of materials is acceptable when air is present in the pore. They used the Darcy's Law which enables to define the frying process more appropriately and requires only the permeability of the material as a measurable single property for the calculation of drying rate. Capillary flow should be used to describe water movement, while Darcy's Law should be used to describe vapour flow in the solid.

d. Vapour convective flux

Datta (2007) has studied the water transport in crust and core regions. He proposed that in the crust region, vapour is driven by the pressure gradient from the evaporation front to the surface. The vapour convective flux magnitudes are comparable to those for diffusion vapour flux, making the convective term important in the crust layer. The magnitude of the convective flux is small but comparable with that from capillary diffusion flux, making both transports mechanisms for water flux important in the core region.

Recently, Halder *et al*. (2007) presented an interesting discussion about the moisture migration throughout the product during frying. They stated that the liquid water that reaches the surface first evaporates and is then convected away. They added that initially, high rate of evaporation near the surface produces large amounts of vapour that cannot escape from the surface due to surface mass transfer limitations, so excess vapour moves towards the core. Since the core is a cooler region, the vapour coming from the surface condenses there, reducing the pressure below ambient pressure. Therefore, as can be seen in figure 5, the liquid saturation in the core increases from 0.3 (raw material) to 0.32 in the first 4 min.

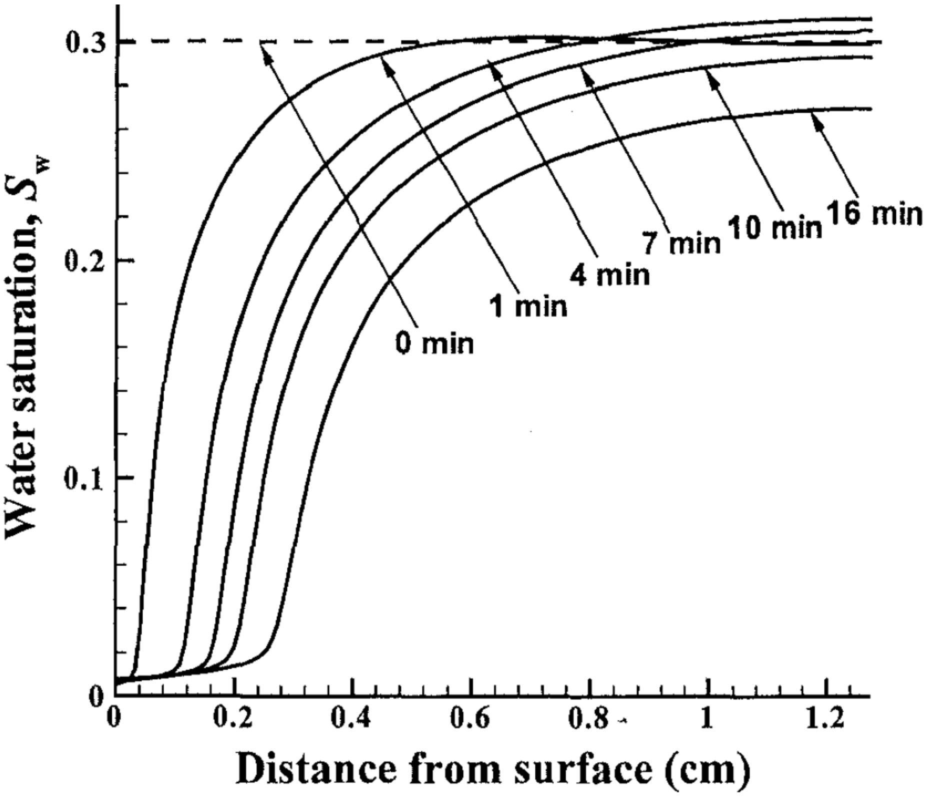


Figure 5. Water saturation profile in a potato slab at various times during frying (According to Halder et al., 2007). Water saturation is defined as the fraction of volume of the pore occupied by water.

3.2.2. Modeling of moisture transfer

Many studies have been published which correlate moisture content with the square root of frying time (Mittelman *et al.*, 1984; Gamble *et al.*, 1987; Keller *et al.*, 1986; and Rice and Gamble, 1989). A simple mathematical model was developed by Mittelman *et al.* (1984), based on the capillary drying of porous materials for the frying. The following equation was proposed:

Eq. 5 $$\frac{dx}{dt}A\rho\lambda = \frac{kA}{x}(T_\infty - T_{evap})$$

where, *x is distance (m), A area of heat and mass transfer (m^2), ρ specific gravity of wet material, k thermal conductivity ($Wm^{-1}K^{-1}$).*

where the cumulative quantity of water evaporated at a given time is:

Eq. 6 $$m = Ax\rho$$

Substitution of two equations and integrating between t = t0 and t = t gives:

Eq. 7 $$m^2 = \frac{2kA^2\rho}{\lambda}(T_\infty - T_{evap})(t - t0)$$

where, *t is time (s), t0 time elapsed before evaporation begins (s)*

A similar equation was proposed by Keller and Escher (1989) for mass transfer during the frying of French fries as:

Eq. 8 $$k(T_\infty - T_s)(t - t_0) = \frac{1}{2}(M^2 - M_0^2)\frac{\lambda + C_p(T_\infty - T_{evap})}{\rho A^2 \varepsilon}$$

where, *Cp is specific heat of vapour (J/kg°C), ε volume fraction of water in potato at time zero (dimensionless), M quantity of water evaporated (kg)*

It is noted this equation of Keller and Escher (1989) differs from Mittelman *et al.* (1984) equation only by the term $C_p(T_\infty - T_{evap})$ which accounts for the energy required to heat the water vapour from the boiling point to the oil temperature.

Rice and Gamble (1989) modelled moisture loss for the process of immersion frying potato chips. A value for the diffusivity was back-calculated for each experimental point using the first term of the solution of the diffusion equation. The diffusivity was found to be relatively constant for frying times between 60 and 240 seconds. They stated that diffusivity and oil temperature could be correlated by an Arrhenius equation as:

Eq. 9 $$D_a = D0\ \exp(-Ea / RT)$$

Where, *Da is diffusion coefficient (m^2/s), D0 a constant (m^2/s),Ea activation energy (J/mol), R universal gas constant (8.314 J/K mol), T absolute temperature (K)*

Kozempel *et al*. (1991) modelled moisture loss using the first term of the solution to the diffusion equation. Similarly, they stated that the diffusivity was a function of oil temperature and could be related to oil temperature using an Arrhenius type equation. Dincer & Yildiz (1996) analysed unsteady-state mass transfer in an infinite sausage cylinder during frying under the conditions of *Biot number* between 0.1 and 100 and *Biot number* higher than 100. They found a diffusivity of 1.312×10^{-7} m^2/s for moisture transfer. Farkas *et al*. (1996), using an assumption that all energy which entered a body was used for vaporization of water, proposed an ordinary differential equation to model moisture loss during frying. While the model was able to fit the experimental moisture data it did not address the transient temperature and moisture profiles in the material body. Moreira *et al*. (1997) presented a model for water loss during frying. Their model did not explain the moving boundary state of frying, as they assumed that the vapour diffuses from the entire body of the product. Later, Ni & Datta (1999) considering a moving front have developed a multiphase porous media model to predict moisture loss, oil absorption and energy transport in a potato slab.

A three-compartment in series model was also reported for describing water losses in deep-fat frying of banana (Courtois *et al*., 1998). Similarly, Costa & Oliviera (1999) have developed a two-compartment model for water loss during potato frying. Moyano & Berna (2002) two models, based on Fick's law were used to describe water loss during frying. The first one is the classic model with an effective moisture diffusion coefficient assumed a constant value. The second model considers that diffusion coefficient varies during the frying process.

3.3. Oil transfer (uptake)

During deep-fat frying, oil affects flavor and texture of the fried food. However, oil uptake in food during frying needs to be reduced for health reasons and this is a major concern in food industry. Although there were some models can predict the heat and water behaviours in the food during frying process, very few studies were performed on oil absorption. Oil content is a major factor affecting the consumer acceptance of fried products and current demand for low fat food products has called for a better understanding of the oil absorption mechanism during frying.

3.3.1. Mechanisms of oil uptakes

Oil absorption mechanisms were vastly discussed in the paper titled “Review of mechanisms, conditions, and factors involved in the oil uptake phenomenon during the deep-fat frying process” (Ziaiifar *et al*., 2008).

3.3.2. Modelling of oil transfer

Modelling of oil absorption is complicated because more than one mechanism may contribute to the total flow, and the contribution of difference mechanisms may change as the frying process proceeds. Kozempel *et al*. (1991) used a zero order model to calculate the oil absorption claiming that this model predict with sufficient accuracy the concentration of oil in French fries, with an error in the prediction of 0.014 g oil/g potato (dry basis). Ateba & Mittal (1994) suggest that foods containing fat undergo two fat transfer periods during the frying process: fat absorption and fat desorption. During the fat absorption period, oil enters ($D=0.28\times10^{-7}$ m^2s^{-1}) into the product. The fat desorption period is marked by the migration of fat from the product to the surroundings due to capillary forces in the pores. Courtois *et al*. (1998) applied a first order differential equation to oil uptake as:

Eq. 10 $$\frac{dC_o}{dt} = k(C_o^{\infty} - C_o)$$

where, C_o *is product oil content (dry – no oil base), k mass transfer coefficient for oil uptake* (s^{-1}), C_o^{∞} *equilibrium product oil content (dry – no oil base) depending to agitation.*

An empirical model followed by first-order kinetics was used to describe oil uptake during frying and cooling (Krokida *et al*., 2001):

Eq. 11 $$O=O_{eq}\,[1 - \exp(-Kt)]$$

where, *O is the total oil content at time t (g oil/g dry solids), Oeq the oil content at equilibrium (or maximum content in dry basis) at t = ∞, t the frying or cooling time and K the specific rate for the first-order model.*

In this model at t = 0; oil content is null, and for long times, oil content becomes the equilibrium value. The relationship for the variation of equilibrium oil content with the frying temperature T is that due to Arrhenius, which has the form:

Eq. 12 $$O_{eq} = ke^{\frac{-Ea}{RT}}$$

where*, k is the pre-exponential factor associated with the collision factor in terms of absolute reaction rates.*

Ni and Datta (1999) developed a multiphase porous media model in which considered that oil transport results from capillarity flow due to the gradient of capillarity force and convective flow. The set of resulting equations was solved by means of a finite difference method and a simulation for a slab of potato showed that the rate of oil uptake is initially higher and then slows down, becoming linear with time.

While several authors tried to model of oil absorption before, model developed by Bouchon & Pyle (2005) represented the most complete and scientifically insight model which integrates the heat, moisture and oil transfer and describes their interrelationship during the different steps of frying process. They stated that oil suction would only begin once a positive pressure driving force had developed.

Eq. 13 $$Q = \frac{\pi r^4 (P_{atm} - P_v + \frac{2\gamma \cos\theta}{r} \pm \rho g h \cos\alpha)}{8\mu l}$$

Where, Q oil volumetric flow (m^3s^{-1}), r the pore radius (m), P_{atm} Atmospheric pressure (Pa), P_v vapour pressure (Pa), γ the surface tension of the oil ($N{\cdot}m^{-1}$), θ the wetting angle between the oil and the solid (rad), ρ oil density ($kg.m^{-3}$), g gravity (ms^{-2}), h the height of the oil in the pore (m), μ the oil viscosity (Pa.s), and l pore length (m)

4. Conclusion

Many attempts were done in order to optimize and control the frying process due to the development and solving a predictive mathematical model for the heat and mass transport in frying. We tried to compare the different models developed for the frying process. Although considerable progress has been made in the understanding and modelling of frying process there is still work needed to improve this process and quality of product due to reduce in oil absorption. Up to now, developed models enable to predict some characteristics of fried product such as internal and external temperature, drying rate and moisture content, while the prediction of oil uptake rate and oil content still remain inaccurate. There is lack of data on critical properties such as permeability of porous food materials.

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Chapter 3

1st part: Porosity Development and its Effect on Oil Uptake during Frying Process

2nd part Oil absorption during cooling of French fries: experimental study

3rd part: Investigation of effective thermal conductivity kinetics of crust and core regions of potato during deep

Results

Chapter three: Results

Introducing text

The literature reviews in the second chapter of this thesis conducted us to study

- The porosity of fried product in order to recognize the effect of porosity development on oil uptake and respond to the question “where the absorbed oil is located in the product?”
- The conditions of cooling period in order to understand the effect of cooling condition in oil absorption and respond to the question “when the oil absorption takes place?”
- The thermal conductivity of crust and core regions in order to collect meaningful data for modeling frying process

At first part, we tried to demonstrate where the oil is absorbed by measuring the product porosity and the absorbed oil content. The effect of frying temperature on oil absorption was investigated in order to clarify its effect which has been the subject of contradiction in literature. The effect of moisture loss on oil uptake especially the replacement of water by oil in the product was also studied. The variations of different product density (apparent density and absolute density) were finally investigated. These density are needed for calculating the portion of pores in the product i.e. porosity.

Part1: Porosity development and its effect on oil uptake during frying process

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Abstract

The objective of this work was to study certain physical properties of French fries such as density and porosity, and their relationship with oil absorption during the frying process. The effects of oil temperature and frying time on moisture loss, oil content and crust thickness were first studied. Changes in apparent density, absolute density as well as porosity during two successive periods of frying process (frying & cooling) were then investigated and possible reasons for these changes were discussed. Finally, the porosity changes were related to oil uptake. Potatoes were cut into rectangular shapes and fried at different oil temperatures (140, 155, 170, and 185°C) for periods ranging from 60 to 240 s. Results showed that during frying, the porosity of the product increases reaching a maximum at the end of frying, whereas during the cooling period, it decreases due to oil absorption and collapse phenomena.

Practical applications

This study shows some physical changes which can be related to the oil absorption during frying process of French fries. Many food research projects attempt to understand oil uptake during the frying process in order to control and reduce the fat content of fried products. The results of this work may lead to find the way(s) to produce less grassy fried product.

Key words:

Deep-frying, structural changes, porosity, oil absorption.

1. Introduction

The structure of fried products depends on frying conditions such as temperature, time, and initial physico-chemical characteristics of the materials. During frying, it is obvious that a porous medium is developed due to structural changes at the surface of the product. Physical properties such as density, shrinkage and porosity are the main factors affecting the texture and transport phenomena of fried foods. Pinthus *et al.* (1995a) studied the mechanism of porosity development. They stated that during frying the water moves from inside the product to the evaporation zone before leaving the product through the surface as vapor. Some of this vapor may, however, remain trapped within the pores. This vapor expands and becomes superheated. It distorts the pore walls and contributes to the development of porosity. The same authors investigated the effect of initial porosity of restructured product (prior to frying) on oil absorption. They concluded that apparent density decreases linearly during frying, showing a much steeper slope when compared with the increase of absolute density. They related this decrease of apparent density to water loss with no identical decrease in product volume. Similarly to their results, Moreira *et al.* (1995) reported that during deep-fat frying apparent density of tortilla chips decreases whereas porosity and oil uptake increase. Saguy *et al.* (1997) stated that product porosity plays an important role in subsequent oil uptake. Linear relationships between oil absorption and porosity have established by several authors (Pinthus *et al.,* 1995a; Moreira & Barrufet, 1998).

In porous materials, moisture transport and oil absorption are more complex phenomena than in non-porous materials. Moisture transport is in fact a capillary mechanism displacing liquid from the core region to the core/crust interface. At this interface, the water is transformed into vapor and is transported throughout the crust (Ni & Datta, 1999). Bouchon & Pyle (2005) have stated that cooling oil absorption is considered to be a pressure driven flow mediated by capillary forces. The porous medium, created during frying, is a solid permeated by an interconnected network of pores (voids), which can be filled with oil and air.

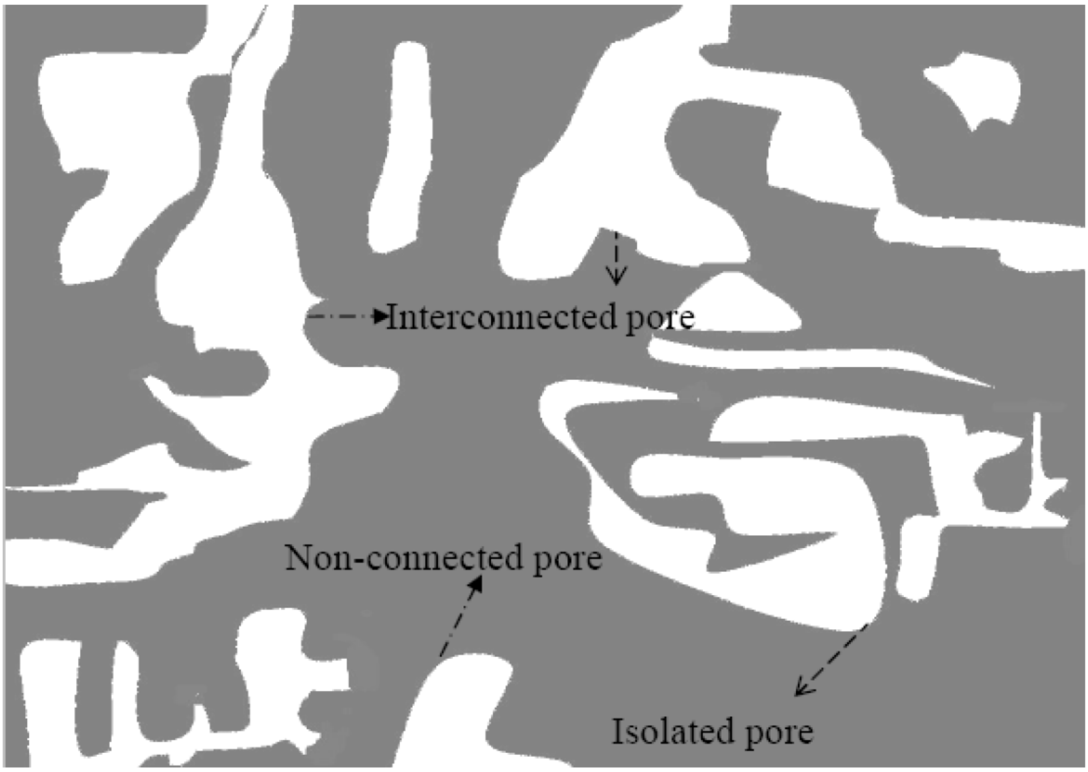


Figure 1. The types of pore present in the fried product; the interconnected and non-connected pores are open pores and the isolated pores are closed ones

Figure 1 illustrates the three possible types of pores: interconnected pores (accessible from many directions), isolated pores (inaccessible), and non-connected pores (accessible from one direction). Kassama & Ngadi (2004) showed experimentally that the interconnected pores contribute to the transport of fluid across the porous medium rather than non-connected pores while the effect of isolated pores on transport phenomena is limited. They used an exponential relationship between porosity and oil uptake during frying of chicken meat while they showed a linear relationship between the pore development and moisture loss.

Over the last two decades reducing oil content of fried products has been of great appeal. Hence, the consumer trend is towards less greasy, healthier products. Oil uptake is mainly a surface phenomenon, as confirmed by many experimental observations (Baumann & Escher, 1995). Concerning the time (moment) of oil absorption, it has been shown that oil does not enter the product at great extent during frying, but is drawn from the oil film on the product when it is removed from the oil bath (Ufheil & Escher, 1996; Moreira *et al*., 1997; Aguilera & Gloria Hernandez, 2000; Bouchon *et al*., 2003; Ziaiifar *et al*., 2007). Moreira *et al.* (1997) showed experimentally that tortilla chips took most of the oil during the first 20 s of cooling when the chips' inner temperature is above that of water condensation. This observation leads to the conclusion that oil uptake during the cooling period takes place by capillary force rather than by vapor condensation. Therefore, development of porous media and oil absorption are not synchronized, i.e. oil enters mainly during the cooling period and partially fills the locations (pores) which are created when the product is still in the hot oil. The two important phenomena in oil absorption are surface rupture and collapse in the product. Surface rupture takes place when the product is in the hot oil and results from increasing internal pressure of the core region due to the heating process. Nagao *et al.* (1997) stated that the final mechanical properties of fried product are more or less influenced by the ruptures on their surfaces. Collapse probably takes place during the cooling of products when water evaporation is stopped and a vacuum is formed. The expression 'collapse' has been used to describe loss of structure, reduction of pore size and volumetric shrinkage in fried/dried food materials (Levi & Karel, 1995).

Collapse phenomenon in fried product can be explained in terms of glass transition. Food materials are amorphous material which exhibit a property named the glass transition temperature (T_g) below which the molecular mobility decreases and viscosity increases drastically (Labuza & Hyman, 1998). Levi & Karel (1995) stated that the collapse temperature and T_g are affected by the same factors and collapse occurs quickly above T_g. The T_g depends on moisture content, increasing with decreasing moisture content (Kawas & Moreira, 2001; Aguillera, 2005). During frying the product temperature, locally, in crust and core region may be below or above the T_g, depending on frying temperature and moisture content. Frying period is followed by a sudden cooling down to ambient temperature. After cooling, core region having high moisture content might remain at a temperature above the glass transition, *i.e.* in rubbery state (Kasahara *et al.,* 2002). Collapse takes place in this state because the food matrix can no longer hold itself and collapses under the force of gravity (White & Bell, 1999). This situation decreases the porosity. In contrast, in the crust region, low moisture content may induce a rubber–glass transition due to its increased T_g. This transformation contributes to the formation of a crispy and porous texture (Saguy, 1997; Mayor & Sereno, 2004). Additionally, Kawas & Moreira (2001) showed that the T_g of tortilla chips increases with oil content. They explained that higher oil content causes more hydrophobic condition which decreases the water plasticizing effect.

In the literature, some studies exist on porosity changes during frying process (Pinthus *et al.,* 1995a; Moreira & Barrufet, 1998; Krokida *et al.,* 2000; Kawas & Moreira, 2001; Kassama & Ngadi, 2004). Moreira & Barrufet (1998) showed the variation of porosity during the cooling period by simulation. Few experimental works have been carried out on porosity variation during the full frying process (frying & cooling) especially concerning the cooling period, which is critical for oil uptake. In order to understand how the mechanism of oil absorption during deep fat frying may change from the beginning of the process to the cooling stage, it is necessary to understand how the pore structure is developed during frying and is filled by oil during the cooling period. The objectives of this study are hence to determine and to quantify porosity, to introduce the important factors on porosity development and to establish the relationships between porosity and oil uptake.

2. Materials and methods

2.1. Frying conditions

Potatoes (Bintje variety) and sunflower oil were the raw materials. Potato tubers were stored at 4°C and 95% relative humidity. The potatoes were cut into $8 \times 8 \times 60$ mm^3 rectangular pieces and samples with the same mass were selected. The samples were washed in distillated water and excess surface water was removed using tissue paper. A domestic deep fat fryer with temperature control of ± 1°C (Seb, France) was used for carrying out frying operations. Fryer capacity was 4 *l*. The fryer was filled with sunflower oil. The potato to oil ratio was kept at 1:100 w/v to prevent temperature variation in the oil bath. The samples were placed in a metal mesh basket and a complementary cover was installed above the basket ensuring immersion frying and preventing samples from floating. The frying was performed at four different temperatures of 140, 155, 170, 185°C. After each frying experiment, the level of oil was checked and the frying oil was changed after 10 h of frying time. All experiments were performed in triplicate and the present results are the mean of the obtained values. The error bars represent standard deviation over the triplicates.

2.2. Analyses

Moisture content was determined by drying the samples down to a constant weight in a convection oven at 105°C (AOAC, 1995). Oil content remained at the surface and oil absorbed by the samples was measured with the method used by Moreira & Barrufet (1998). The surface oil was washed out in a beaker using petroleum ether immediately after frying. For frying time (60, 120, 180, and 240 s), the sample washing (surface oil removal) was performed quickly (about 1 second) after withdrawal of the samples from the fryer. For cooling time, which starts after 240 s of frying, the samples were washed in petroleum ether once the defined cooling time had ended (0-240 s). In each experiment, only one strip was washed for each analysis. The oil which dropped into the beaker was collected by evaporating the petroleum ether, and this oil was defined as surface oil content. The remaining oil in the sample was quantified as absorbed oil content and was determined using soxhlet extraction with petroleum ether after oven drying (5 h at 105°C). To obtain profiles of oil and moisture, French fries were cut off into 5 mm thick slices, and the oil and moisture contents were measured for each slice cut (Figure 2). All moisture and oil content values presented in this work are based on oil free dry matter. The crust thickness of fried samples was measured by carefully separating the core from the crust by scratching the core with a scalpel (Pinthus *et al.*, 1995b). Special care was taken to remove only the soft layer which did not visually adhere to the crust. Ten thickness measurements were carried out on different crust sections utilizing a micrometer.

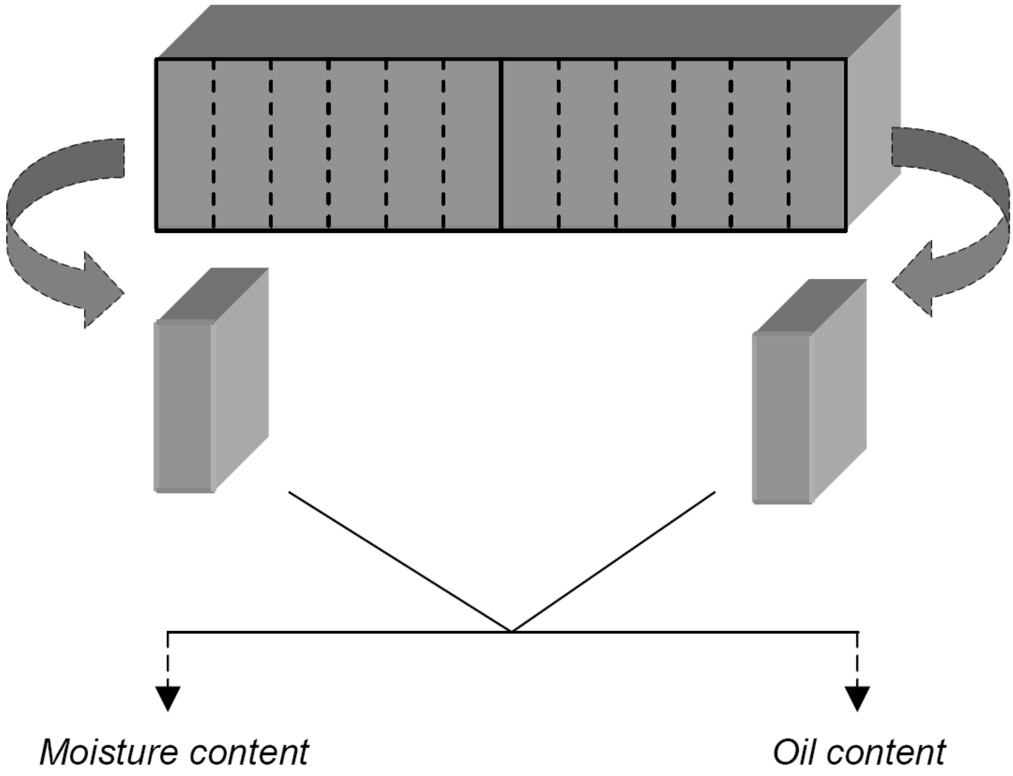


Figure 2. The method to determine the profiles of water and oil in the product

The absolute density refers to density calculated on the basis of volume excluding pores and inter-particle spaces. The apparent density is based on the total volume including the pores but excluding the inter-particle spaces. Before density measurements, the surface oil was removed from the samples by washing in petroleum ether. The prepared samples were put in Petri dishes to prevent the moisture adsorption by the samples. Apparent density of samples (ρ_{ap}) was measured using Pyrex® glass pycnometer. An empty glass pycnometer (approx. 28 ml), with n-heptane were weighed (M_1) using an electronic balance with 10^{-4} g precision. The samples were weighed precisely (M) and then transferred into the pycnometer. The pycnometer was then filled with n-heptane. The outside of pycnometer was dried and the weight of the pycnometer with n-heptane and sample (M_2) was determined. The apparent volume of sample (*V*) was calculated using:

$$V = \frac{M + M_1 - M_2}{\rho} \tag{1}$$

where, ρ is the density of n-heptane. Having the mass and the volume of sample, apparent density was calculated as:

$$\rho_{ap} = \frac{M}{V} \tag{2}$$

Absolute density (ρ_{ab}) of the samples was measured with a pycnometer using compressed air for pressure measurement, with an accuracy of 0.05 *ml*. Air fills almost all accessible pores within the sample. This method was not able to quantify the closed pores. Porosity (*P*) can be calculated as follows:

$$P = 1 - \frac{\rho_{ap}}{\rho_{ab}} \tag{3}$$

In this work, the calculated porosity, named also apparent porosity, was related to the accessible (open) pores of the samples and not to those which were closed. Shrinkage of samples was calculated by the following equation:

$$S(t) = \frac{V_0 - V(t)}{V_0} \tag{4}$$

where, $S(t)$ is shrinkage, V_0 the volume of the initial samples and $V(t)$ the volume of the samples at time *t*. These volumes were measured using a Pyrex® glass pycnometer.

3. Results and discussions

3.1. Moisture loss and oil uptake

3.1.1. Moisture loss during frying

The moisture content histories of French fries at different temperatures are shown in Figure 3. The moisture content of the samples decreased during frying. As expected, water evaporation took place quicker when the higher temperatures are applied. There are important differences between 140, 155 and 170°C, while the higher temperature of 185°C has no additional effect on moisture reduction when it is compared with 170°C. This observation is in agreement with the results of Vitrac *et al.* (2000).

3.1.2. Oil absorption during frying

Generally, the longer the product remains in the fryer the more the oil is absorbed. In agreement with several authors (Aguilera & Gloria-Hernández, 2000; Bouchon *et al.*, 2003; and Ufheil & Escher, 1996; Moreira *et al.*, 1997), Figure 4a illustrates that oil content was high even for short frying times showing the importance of oil adhering to the surface of the product on final oil content of fried samples. Gamble *et al.* (1987) showed a linear relationship between oil content and water loss. They added that this relationship was not affected by frying temperature.

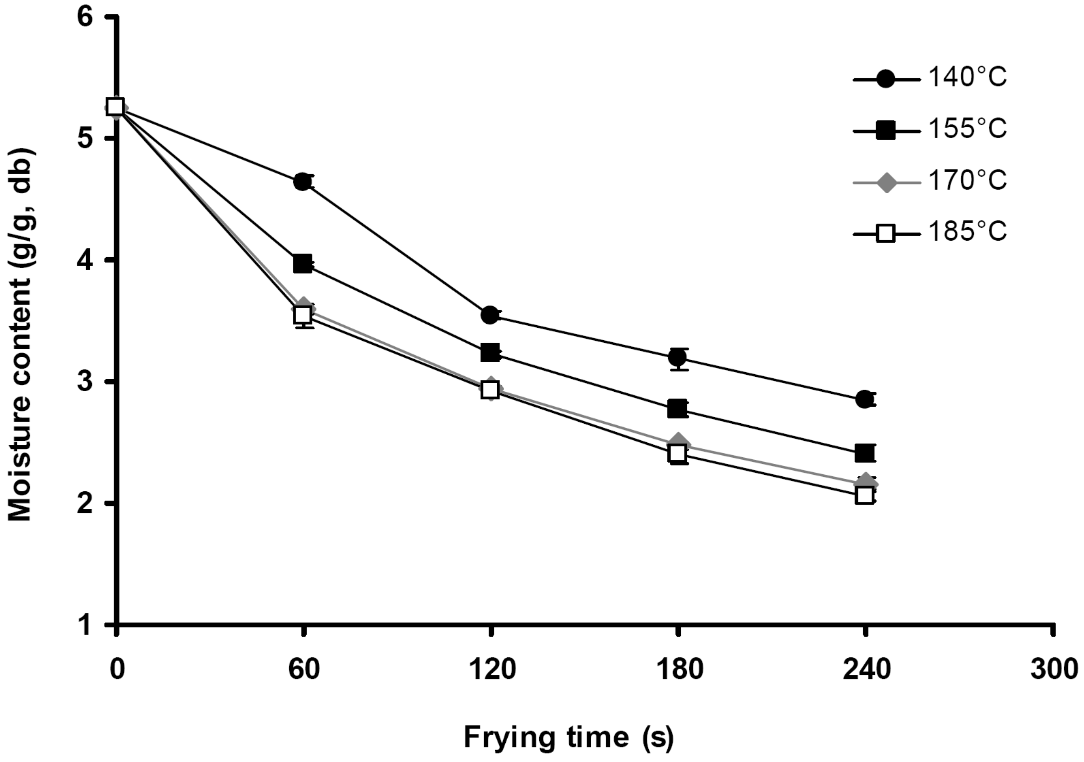


Figure 3. The moisture content of French fries during frying at 4 different temperatures

Concerning the effect of oil temperature (positive or negative) on the oil content of the product there are some contradictions in the literature (Ziaiifar *et al.*, 2007). Once oil content is studied as a function of frying time (Figure 4a), the effect of frying temperature becomes negligible, i.e. there are no visible differences at any given time between the oil content of products fried at 140°C or 185°C. However, as a function of moisture content, as shown in Figure 4b, the oil content is higher in the product fried at a lower temperature. This result agrees with the findings of Baumann & Escher (1995), Moyano & Berna (2002), Moyano & Pedreschi (2006) and Duran *et al.* (2007). Baumann & Escher (1995) compared oil uptake for frying at different oil temperatures to equal moisture contents. They showed that when a final moisture content of approximately 0.02 kg/kg is considered, an oil temperature at 150 °C needs a longer frying time as compared to 180 °C which in turn results in a significant increase of oil content.

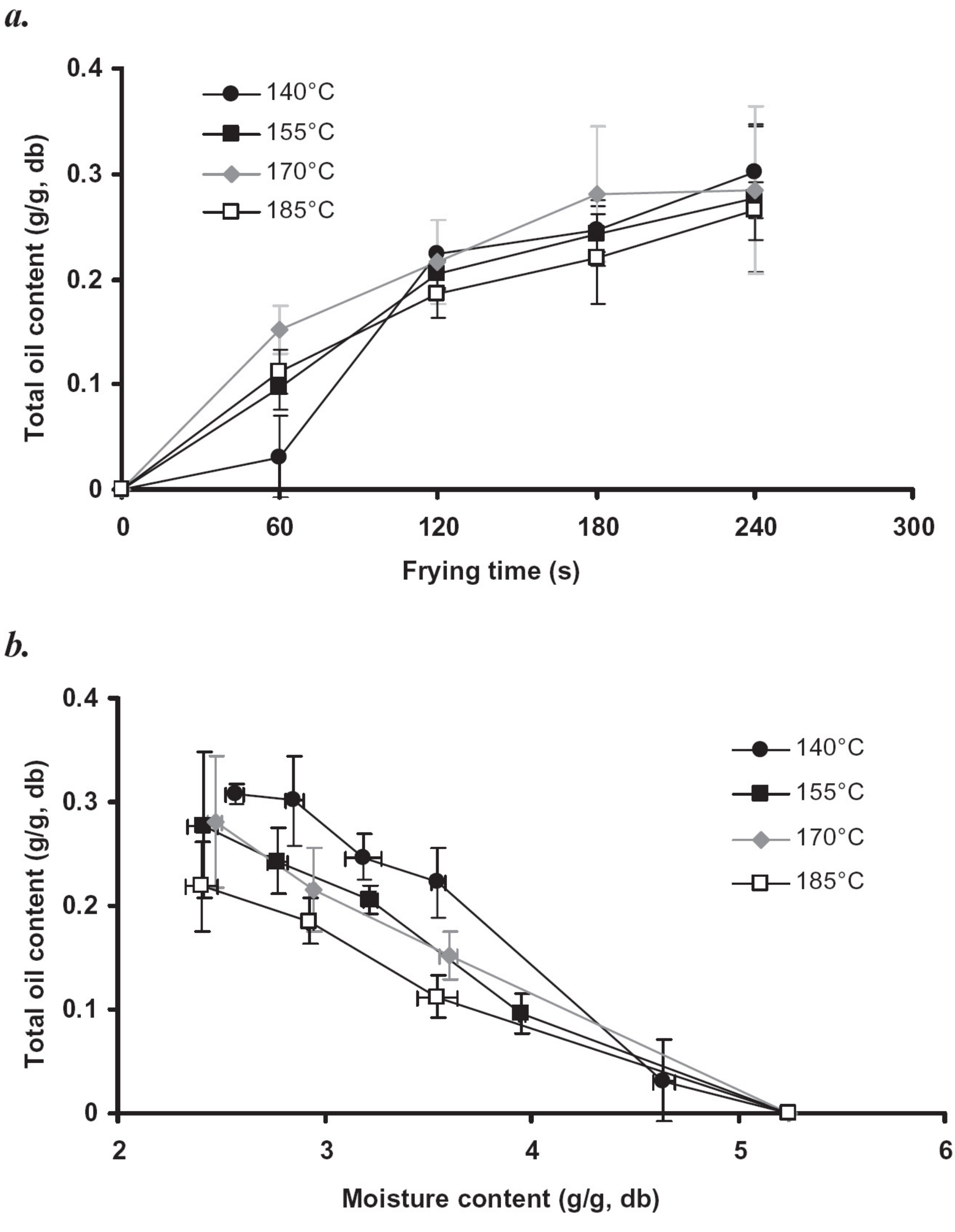


Figure 4. The effect of oil bath temperature on total oil content: a. total oil content vs. frying time, b. total oil content vs. moisture content. Note: oil content is measured after the cooling period.

Recently, in agreement with their result, Moyano & Pedreschi (2006) demonstrated that for the potato slices (unblanched and without pre-drying), oil uptake increased as the frying temperature decreased from 180 to 120 °C. Figure 4b shows that the samples fried at 140°C have about 30% more oil content in dry base than those fried at 185°C in the same moisture content of 2.5 (g/g, dry base). During frying at low temperatures, oil absorption takes place not only during cooling period but also to some extent during frying period; this fact can be explained by the fact that low frying temperatures and thus weak water flows lead to the formation of a crust with a structure favorable to oil absorption during frying period. On the other hand, higher temperatures produce harder and tougher crust, promoting an increased resistance to transfer, which reduces surface diffusivity (Moyano & Berna, 2002). This result shows the importance of a higher energy supplement during frying on the reduction of oil content of the fried product. However, the interest of increasing the temperature even higher is limited because of the formation of hard dark brown crust (Taiwo & Baik, 2007).

3.1.3. The VR factor

Pinthus *et al.* (1995a) showed experimentally that the basic physical effect of deep fat frying on the product is partial water replacement by oil. They developed a criterion, which would alleviate the dependency of oil uptake on moisture. The "oil uptake ratio," UR, criterion was defined as:

$$U_R = \frac{Oil\ content\ (g)}{Water\ loss\ (g)} \qquad (5)$$

In this study, as the volume replacement of water by oil is of interest rather than the mass replacement, we added a new factor named V_R similar to U_R but in volume base. V_R value expresses the volume ratio between the amount of oil uptake and water removed, defined as:

$$V_R = \frac{Oil\ content\ (cm^3)}{Water\ loss\ (cm^3)} \qquad (6)$$

Figure 5 shows that only 5-14% of evaporated water is replaced by oil, depending on the frying conditions (temperature and time). This result can be explained by this fact that as oil absorption takes place during the cooling rather the frying period (Moreira & Barrufet, 1996), the oil which can be absorbed by French fries is limited to the oil adhering to the surface. During the first minute of frying, the V_R value increases quickly; this increase continues during the second minute of frying but at a reduced rate (except at 140°C). After two minutes of frying, this value does not change and remains approximately constant at 0.15, 0.11, 0.11, and 0.9 for 140, 155, 170, and 185°C, respectively. As shown in Figure 5, the French fries fried at higher temperature show lower V_R value. This is because of the fact that more water is evaporated at higher temperature while the absorbed oil is approximately the same at a given time.

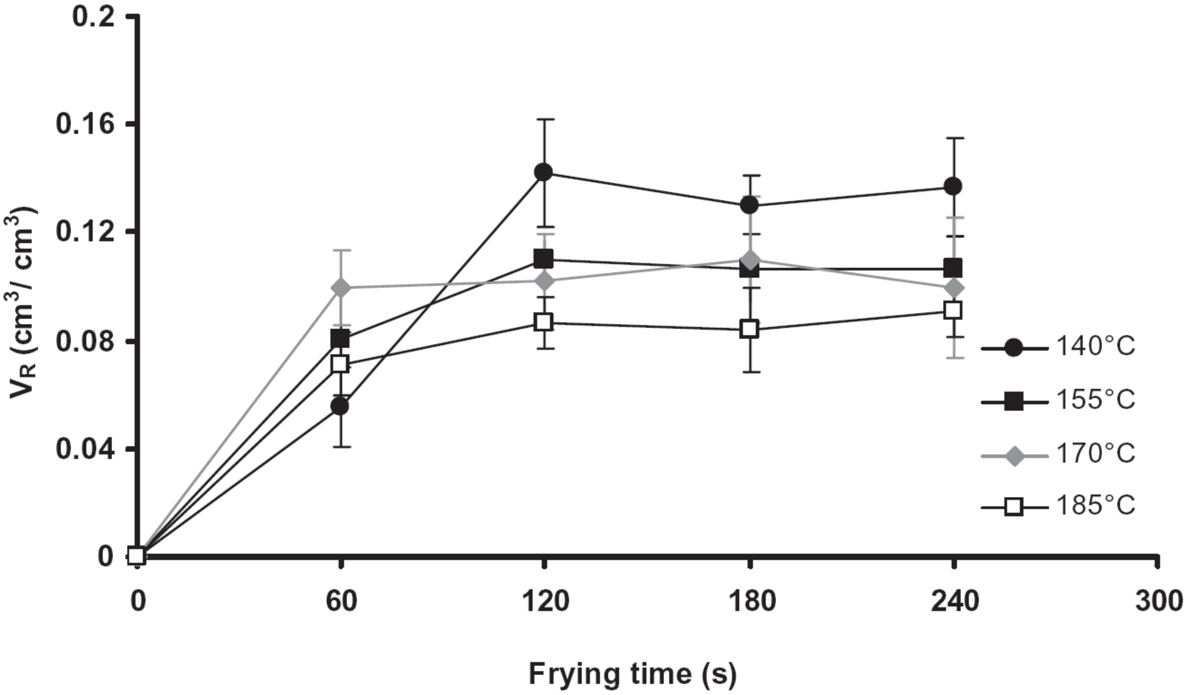
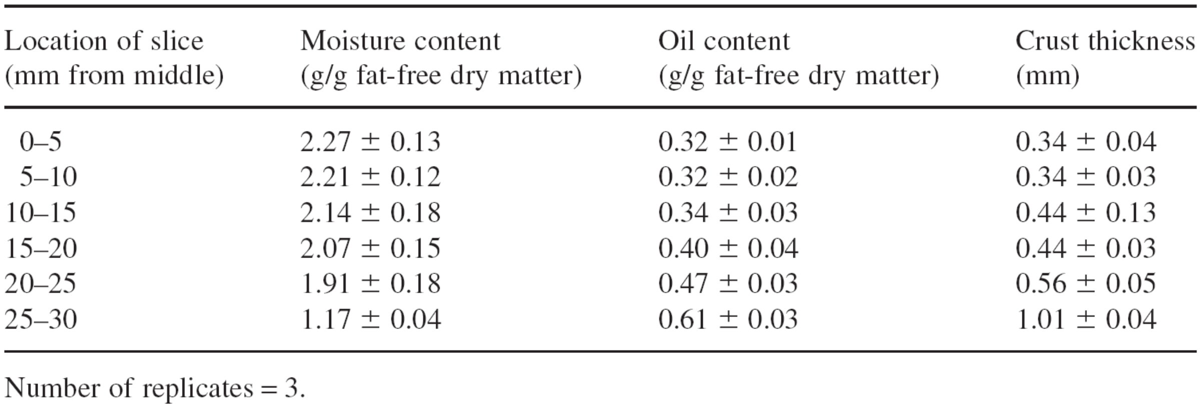


Figure 5. The oil content on water loss (V_R value) as a function of frying time



Location of slice (mm from middle)	Moisture content (g/g fat-free dry matter)	Oil content (g/g fat-free dry matter)	Crust thickness (mm)
0–5	2.27 ± 0.13	0.32 ± 0.01	0.34 ± 0.04
5–10	2.21 ± 0.12	0.32 ± 0.02	0.34 ± 0.03
10–15	2.14 ± 0.18	0.34 ± 0.03	0.44 ± 0.13
15–20	2.07 ± 0.15	0.40 ± 0.04	0.44 ± 0.03
20–25	1.91 ± 0.18	0.47 ± 0.03	0.56 ± 0.05
25–30	1.17 ± 0.04	0.61 ± 0.03	1.01 ± 0.04

Number of replicates = 3.

Table 1. Moisture, oil and crust thickness profiles in French fries fried at 170°C for 240 s

3.1.4. Moisture, oil and crust thickness profiles in the fried product

Table 1 shows moisture, oil and crust thickness profiles in French fries fried at 170°C for 240 s. The dehydration of potato and oil uptake in the product do not take place in the same way at the middle and extremity of the product. Dehydration is stronger at the two extremities of the product resulting in thicker crust, as explained by other authors (Yamsaengsung and Moreira, 2002; Kawas and Moreira, 2001; Rajkumar *et al.*, 2003). Furthermore, the oil content in these sections is higher than in the middle part. This point can be a crucial in modeling of frying processes, especially in thick products. Therefore, most models suppose the product as infinite geometry.

3.2. Crust and core characteristics

The crust is one of pleasurable characteristics of fried foods. Its formation influences mass transfer phenomena and physical properties of fried products (Keller *et al.*, 1986). Farkas *et al.* (1996) stated that during frying, two regions separated by a moving boundary (crust and core) can be distinguished. Frying of potato strips showed an initial stage in which the whole tissue softened, the core became cooked and crust formation started, and a later stage in which the crust was developed and hardened progressively (Pedreschi *et al.*, 2007). Aguilera & Gloria-Hernandez (2000) showed that the absorbed oil is located on the crust, especially in its pores and canals. Later, Bouchon *et al.* (2001) stated that the distribution of the absorbed oil in the crust depends on its porous structure as the oil absorption happens by suction, not by diffusion. Luyten *et al.* (2004) stated that the combination of starch and oil during the frying process resulted in amylose-lipid complexes much stronger near the surface than in the core of the product. Figure 6 shows that the thickness of crust increases with both the increase of frying time and frying temperature. Table 2 shows some characteristics of core and crust regions after 240 s of frying at 170°C. The crust is partially dehydrated and represents more than 50% of the total initial solid content of the raw potato in this case. Its apparent density is approximately half of the core, while its absolute density is higher than that of the core. The main difference between the core and the crust is in their porosity. The crust is nearly 6 times more porous than the core, showing its capacity for oil absorption.

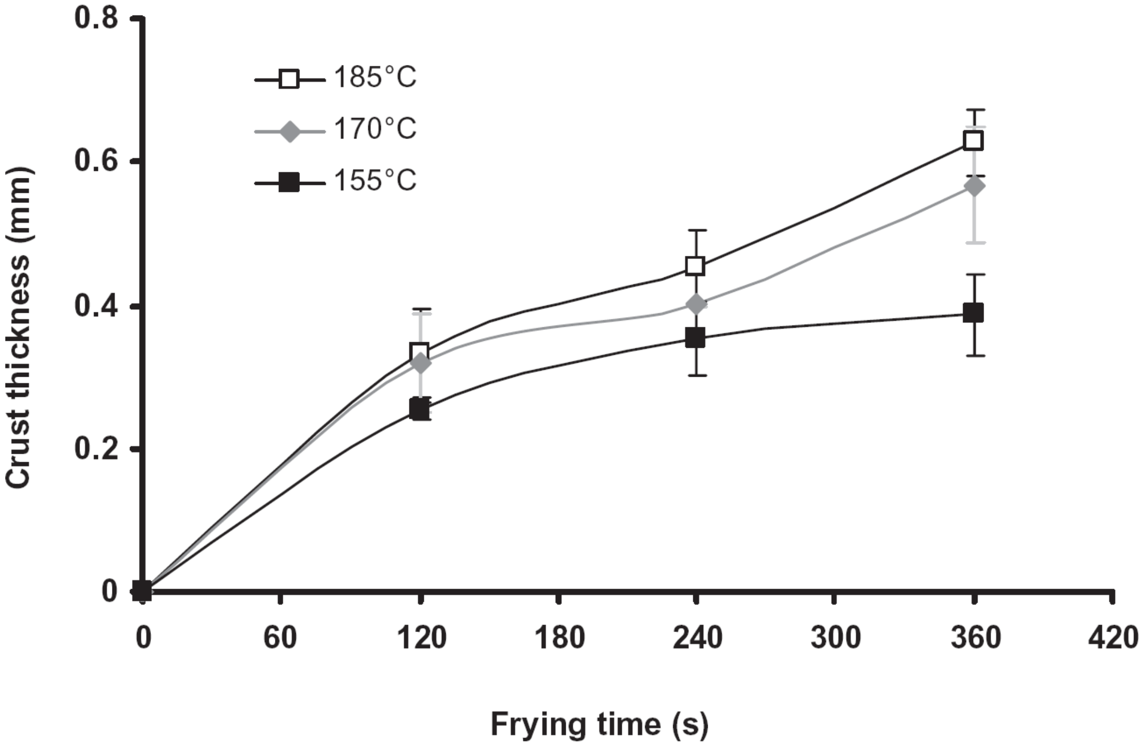
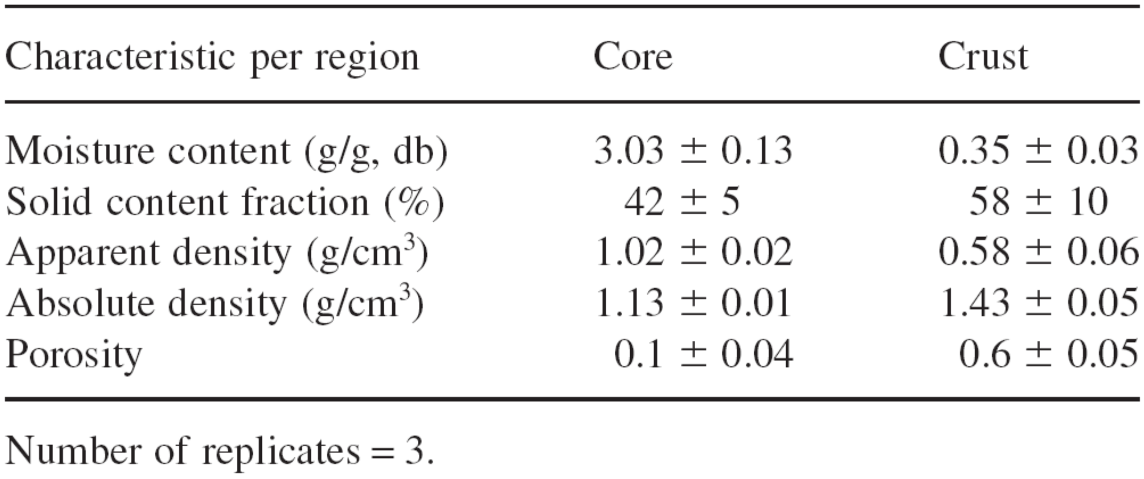


Figure 6. The crust thickness during frying of French fries



Characteristic per region	Core	Crust
Moisture content (g/g, db)	3.03 ± 0.13	0.35 ± 0.03
Solid content fraction (%)	42 ± 5	58 ± 10
Apparent density (g/cm^3)	1.02 ± 0.02	0.58 ± 0.06
Absolute density (g/cm^3)	1.13 ± 0.01	1.43 ± 0.05
Porosity	0.1 ± 0.04	0.6 ± 0.05

Number of replicates = 3.

Table2. Some physical characteristics of core and crust in French fries fried at 170°C for 240 s

3.3. Shrinkage

Aguilera (2005) stated that shrinkage takes place during dehydration of high moisture food when the viscoelastic matrix contracts in the pores previously occupied by water. The shrinkage was investigated as a function of frying time (Figure 7a) and moisture content (Figure 7b). As shown in Figure 7a, in the early stage of frying the shrinkage takes place quickly. It then slows down until the moisture content of the product reaches about 3 (g/g, free oil dry base). Finally, the shrinkage is stopped. This stopping can be explained by the formation of a rigid crust resisting to further volume reduction. Frying at higher temperatures resulted in more shrinkage for the same frying time. Figure 7b shows that shrinkage is strongly related to moisture content. This result is in agreement with results of Kawas & Moreira (2001); Garayo & Moreira (2002); Rajkumar *et al.* (2003) and Taiwo & Baik (2007).

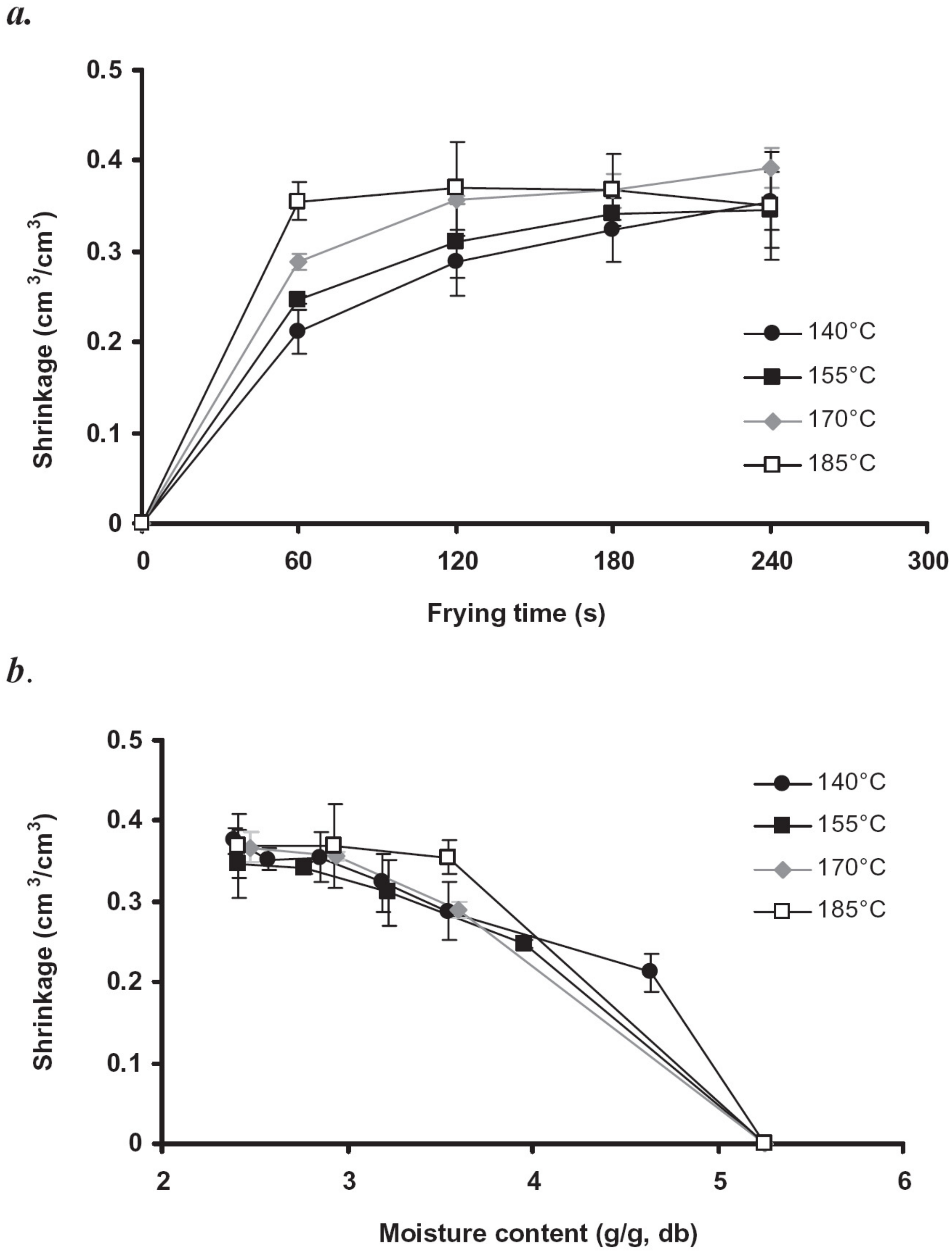


Figure 7. The shrinkage of French fries: a. the shrinkage as a function of frying time, b. the shrinkage as a function of moisture content

3.4. Physical properties changes during frying and cooling

3.4.1. Apparent density

Figures 8a and 8b show the variation of apparent density of French fries as a function of moisture content and process time, respectively. Figure 8a shows that apparent density does not change until the moisture content reduces to approximately 3.75 (g/g, oil free dry base). Therefore, moisture content of 3.75 can be regarded as a critical value for apparent density change of French fries. Figure 8b shows the apparent density changes during frying and cooling. During the frying period, apparent density decreased at all frying temperatures. Apparent density values ranged from 1.04 to 1.06 g/cm^3 at the raw material and 0.96, 0.88, 0.89, and 0.84 g/cm^3 after 240 s of frying at 140, 155, 170, and 185°C, respectively (Figure 8b). Frying temperature has a negative effect on apparent density. These results agree with those of Krokida *et al.* (2000), Kawas & Moreira (2001), and Taiwo & Baik (2007). The decrease in apparent density has been related to the combination of pore formation (puffing of sample), water loss and oil uptake. During the first minute of frying, apparent density hardly changes, which can be explained by the fact that, at the beginning of frying, the ratio of mass loss (due to water evaporation) to volume loss is one which results in constant apparent density. Later, shrinkage practically ends (Figure 7b) while water loss continues. This situation results in a reduction of apparent density. Frying at higher temperatures resulted in a lower apparent density probably due to accelerated water loss resulting in more pore formation. As shown in Figure 8a, the frying temperature has no effect on apparent density when it is investigated as a function of moisture content.

During the cooling period, the apparent density varies in the opposite way to that of the frying period. As shown in Figure 8b, during the early stage of cooling, the apparent density of the samples increases. It reaches a maximum of 1.04 after 80 s of cooling, 0.99 after 80 s, 0.92 after 80 s, and 1.00 g/cm^3 after 140 s of cooling, respectively for 140, 155, 170, 185°C of frying temperatures. Higher frying oil temperatures during frying cause longer time for apparent density to reach a constant value during cooling.

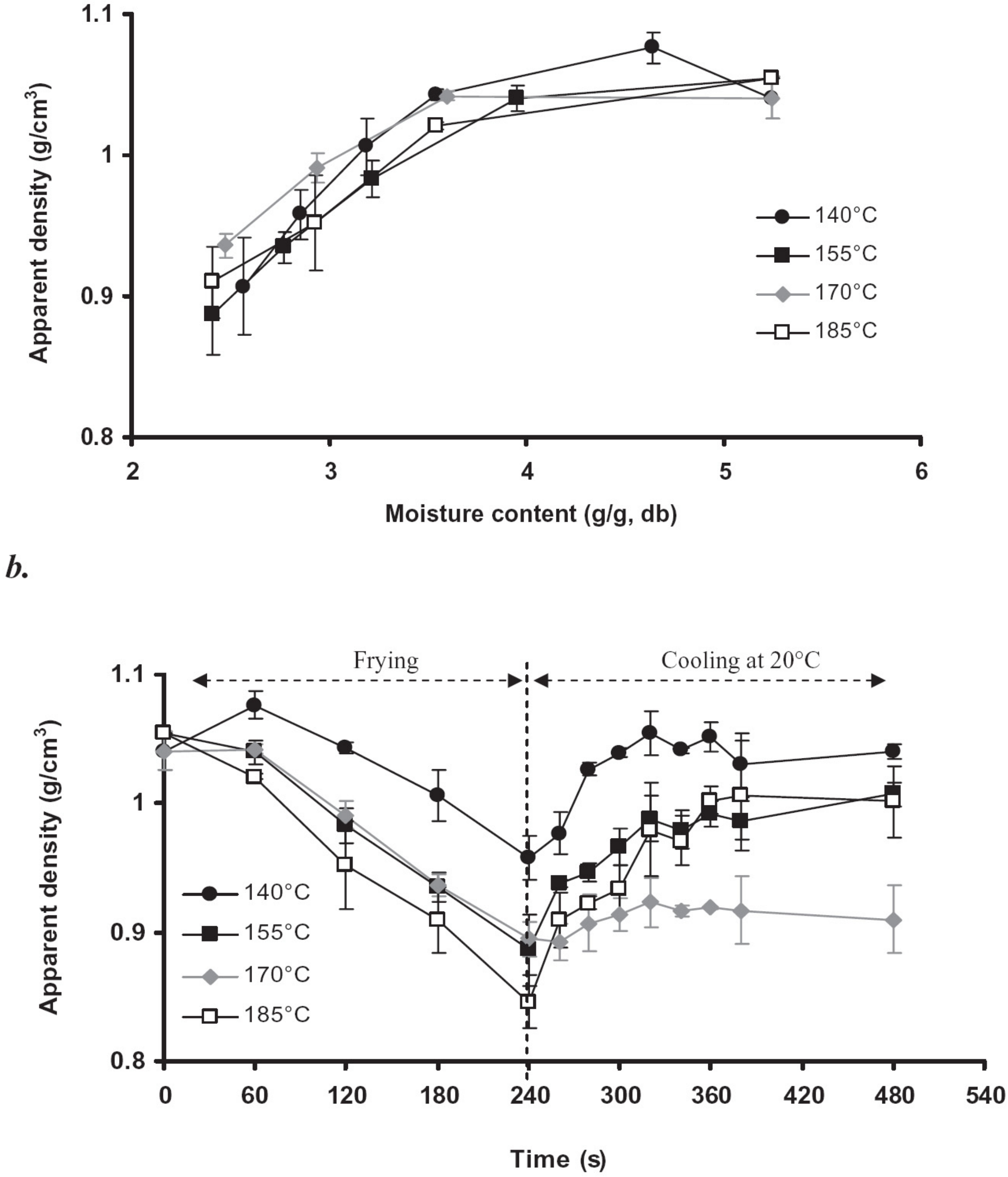


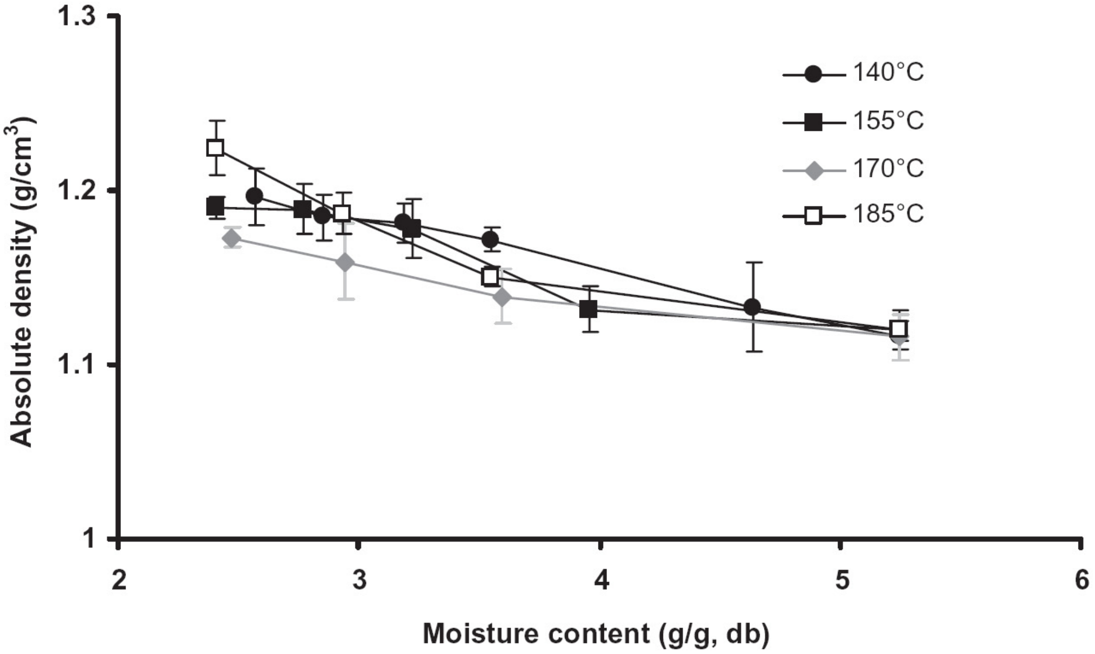
Figure 8. The variation of apparent density: a. the apparent density as a function of moisture content, b. the apparent density as a function of frying and cooling time

3.4.2. Absolute density

Figures 9a and 9b show the variation of absolute density of French fries as a function of moisture content and process time, respectively. The absolute density values were about 1.12 for raw potato and 1.18, 1.20, 1.22, and 1.26 for 240 s of frying at 140, 155, 170, 185°C, respectively showing that absolute density increases with higher frying temperatures and longer duration (Figure 9b). Krokida *et al.* (2000) stated that bath oil temperature significantly influences absolute density. They added that when the temperature increases, the product absolute density decreases due to the higher oil content and lower water content. Our results, contradicting theirs, show that higher oil temperatures induce higher absolute density. Raw potato having an absolute density of about 1.1 g/cm^3 includes dry matter (mainly starch) with density approx. 1.55 g/cm^3 (20%), water with density approx. 1 g/cm^3 (80%) and oil with density approx. 0.9 g/cm^3 (0%). As explained before, frying at higher temperature causes more water loss and less oil content. When more water is removed, the absolute density increases because of the difference in dry matter density and water density (removing the lighter element). In addition, less oil content causes higher absolute density similarly due to lower density of oil.

Figure 9b shows that the absolute density does not change during the cooling period. The reason for this stationary behavior of absolute density may depend on two phenomena which take place during cooling: collapse in isolated pores and oil absorption. Collapse in isolated pores (which are not accessible to measure) causes volume reduction resulting in absolute density increase while the oil absorption causes absolute density decrease because the density of the oil is lower than that of the sample. The balance between these two phenomena is assumed to be responsible for the behavior of absolute density.

a.



b.

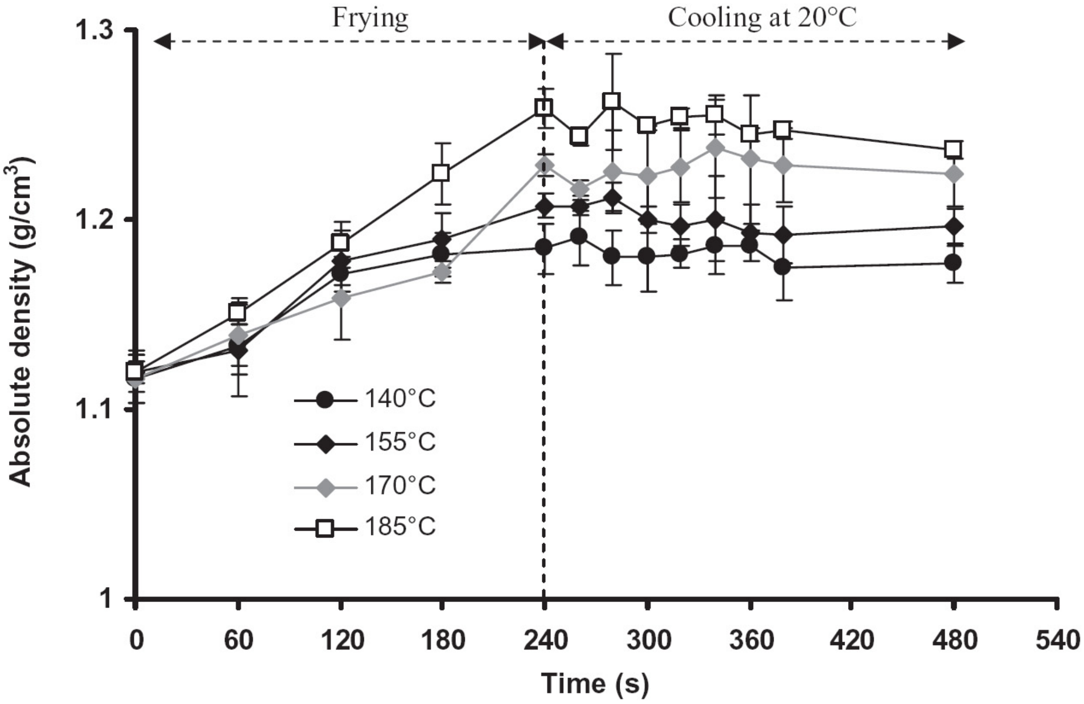


Figure 9. The variation of absolute density: a. the absolute density as a function of moisture content, b. the absolute density as a function of frying and cooling time

3.4.3. Porosity

Porosity is a global characteristic of food materials, which provides the volume fraction of total pores compared with the total volume (Rahman, 2001). Rahman *et al.* (2005) showed that the porosity changes significantly with moisture content. In agreement with their study, Figure 10a shows that the porosity is effectively related to moisture content. Kawas & Moreira (2001) stated that the porosity of tortilla chips increased by about 70% during frying. As shown in Figure 10b, higher bath temperatures cause faster pore formation due to accelerated water evaporation during the frying period; this condition increases the porosity. At the end of frying, porosity reached to a maximum value of 0.19, 0.25, 0.27, and 0.33 for 140, 155, 170, 185°C of frying temperatures, respectively. As described by Kawas & Moreira (2001) and Krokida *et al.* (2000), this result can be explained by water loss, apparent density decrease and crust formation. During the cooling period, due to oil filling and collapse, the porosity decreases 0.12, 0.17, 0.25, and 0.19 after 40, 80, 40, and 120 s of cooling time, respectively. Pores can be filled with oil, water vapor or a mixture of the two depending on the periods of the frying process (frying and cooling periods). During the cooling period, the created pores are filled by oil and partly closed by collapse phenomenon. An unexpected behavior was shown in the French fries fried at 185°C in Figures 8 and 10. This behavior may be explained by the fact that a more porous structure, formed at a higher temperature, is more influenced by the collapse phenomenon.

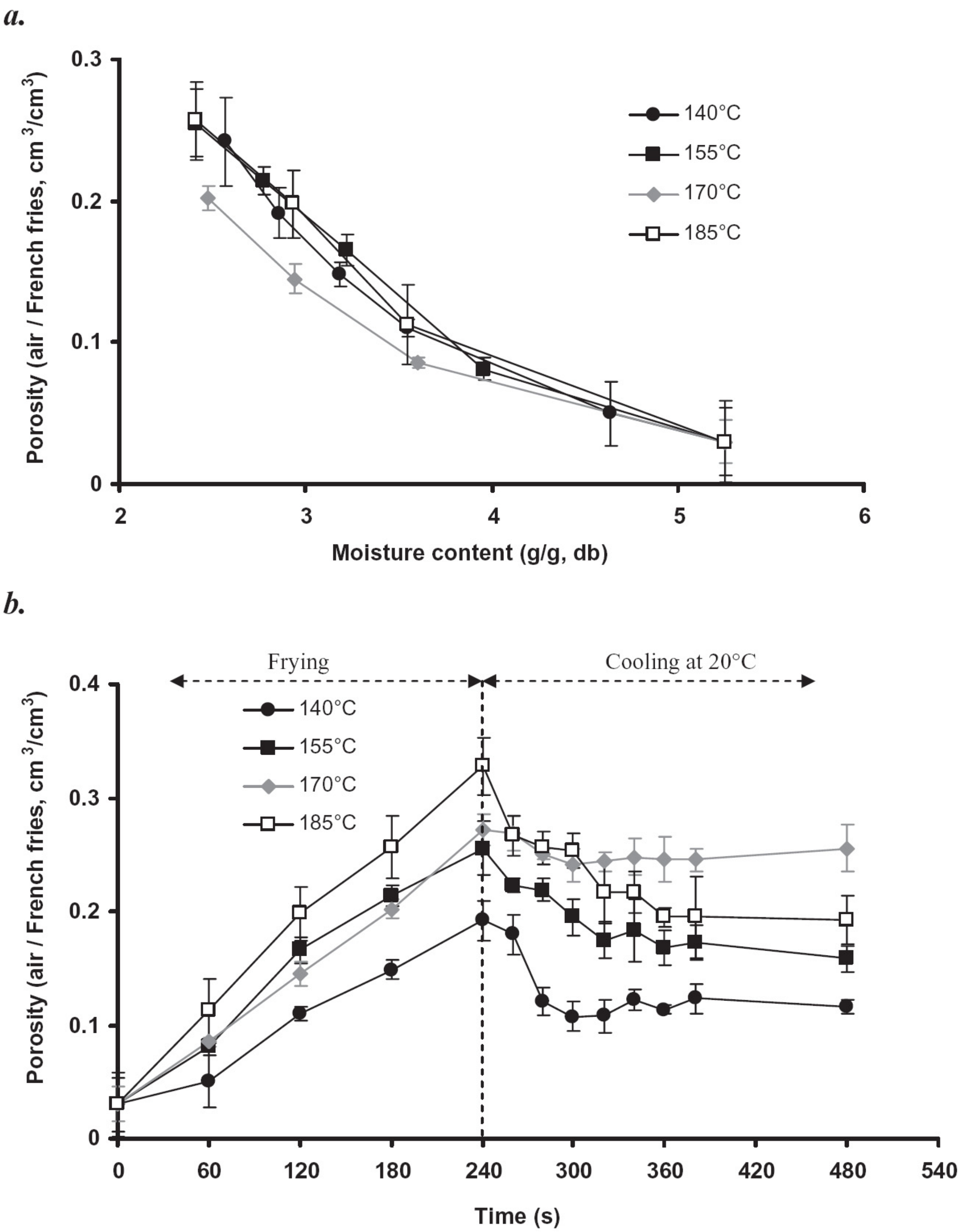


Figure 10. Porosity variation: a. the porosity as a function of moisture content, b. the porosity as a function of frying and cooling time

3.5. Porosity and oil uptake

The variation in porosity and absorbed oil content (volume base) of French fries during frying and cooling are shown in Figure 11. During the frying period, the porosity increases and reaches a maximum value, while during cooling it decrease. The rate at which porosity decreases during cooling is higher than its rate of increase during frying. The oil absorption occurs at a lower rate during the frying than the cooling period. The absorbed oil content can influence the porosity due to its ability to fill the pores in the product. During the frying period, the absorbed oil content is not high enough to fill the pores which are continuously forming. During the cooling period, the absorbed oil decreases porosity. It is believed that the collapse also plays an important role in porosity decrease because the volume of the absorbed oil is low to explain the decrease in porosity. As shown in Figure 11, during cooling porosity decreases by about 0.13 units (from 0.33 to 0.20). Only 0.08 units (60%) of porosity decrease are related to oil filling and the rest is probably due to collapse phenomenon. At higher temperatures, crust is thicker (Figure 6) and more pores are formed (Figure 10). Therefore, in this condition, it is expected that more oil is absorbed by the product. Figure 4b displays unexpectedly higher oil content at lower temperatures. This situation may be explained by the fact that at lower temperatures, along with these physical properties (crust thickness and porosity), the oil entering into the product during frying period plays an important role in final oil content.

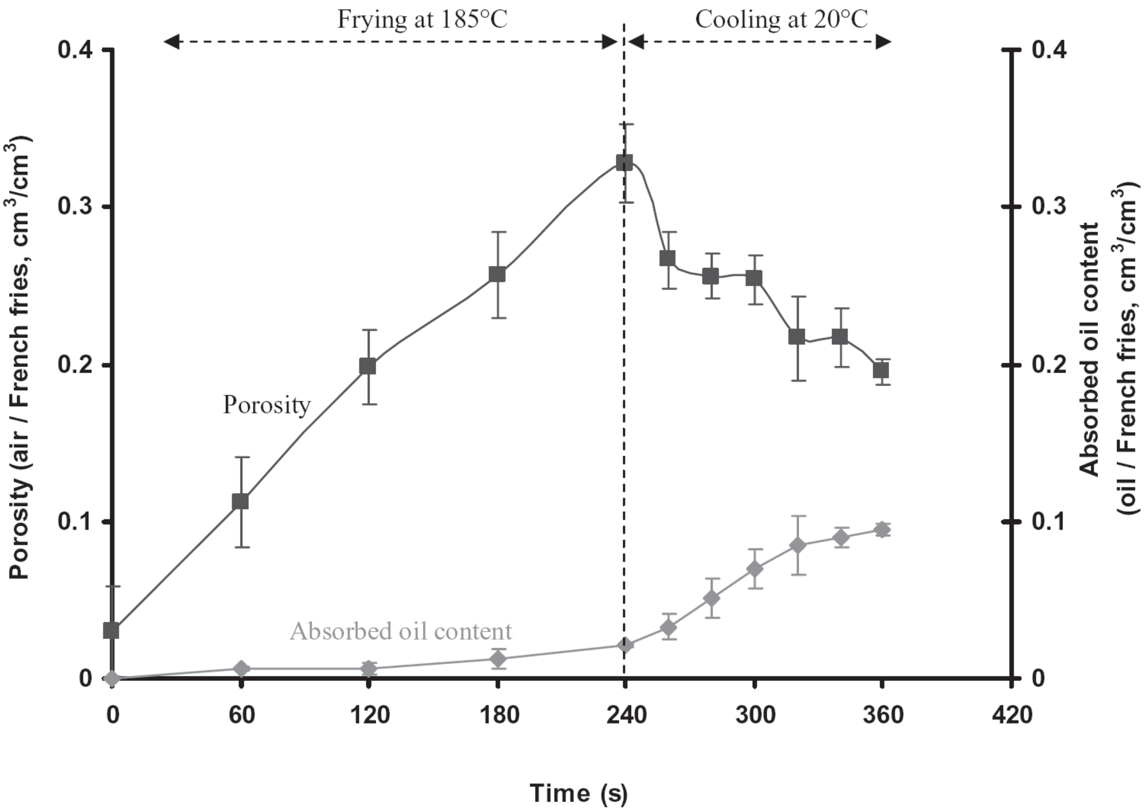


Figure 11. Porosity and absorbed oil contents of product fried at 185°C for 240 s frying followed by 120 s cooling at 20°C

4. Conclusions

Oil uptake increased as the oil bath temperature decreased from 185 to 140°C. Potato structure changes with frying time; as crust thickness and absolute density increase whereas apparent density decreases. The porosity increases during frying due to forceful water evaporation and pore formation, and reaches a maximum at the end of frying period. However, during the cooling period, it starts to decrease as a result of the absorbed oil implanted in the pore spaces and collapse phenomenon. The results of this study suggest that the characterization of the product microstructure appears to be a determining factor in the description of oil uptake.

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CONNECTING TEXT

As a second part of the results, experimental studies were performed in order to demonstrate the oil absorption period and the factors determining this absorption. It has been shown in literature that the oil absorption mainly takes place during cooling period. Therefore we tried to focus on this period and investigate the condition and factors on oil uptake.

The main factor which influences the cooling conditions is the temperature at the interface between the adhered oil and product surface i.e. where oil absorption takes place. Therefore, it is decided to measure the temperature at the surface of product during cooling period. We measured also the variation of different physical properties of adhered oil regarding the temperature. The data obtained from these measurements were useful to determine the conditions of oil uptake and the important mechanisms of oil absorption.

At the end of this part, some experimental works were performed in order to decrease the oil absorption and reduce the final oil content in the fried product. The methods were the vacuum cooling and the centrifugation of product during cooling in order to eliminate the oil from the product and decrease the oil content.

Part 2: Oil absorption during cooling of French fries: an experimental study

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Abstract

Studies reported in literature have shown that the oil absorption takes place from the adhered surface oil into the product mainly when it is removed from fryer. In this work, at first, the physical properties of this oil were investigated in order to understand the conditions in which this oil is absorbed. During the cooling period, the adhered oil temperature decreases due to the temperature gradient with the cooling air. As results, the oil density and oil viscosity increase; this fact influences the oil absorption rate. In the second part of this paper, the cooling period was carried out in different conditions of pressure and centrifugation and the final oil contents of product were compared. The centrifugation can considerably decrease the oil content of product while the effect of vacuum cooling was lower.

1. Introduction

The mechanism of oil uptake has been studied primarily to reduce the final oil content of fried product. However, in spite of all these efforts, fried products still contain significant amounts of oil. Frying process involves two periods, one when the product in fryer (frying period), the other when the product is removed from fryer (cooling period). The cooling period was been highlighted as the oil absorption period by several authors (Ufheil & Escher, 1996; Moreira *et al*., 1997; Bouchon & Pyle, 2005; Ziaiifar *et al*., 2008). Moreira & Barrufet (1998) stated that during frying only 20% of the total oil content was absorbed by the tortilla chips, and the rest (80%) remained at the chip's surface. The chips have high surface to volume ratio when compared with thicker products such as French fries. Therefore, the absorbed oil content during frying period will be lower in these products. Dana & Saguy (2006) stated that 70 to 80% of the total oil uptake was oil wetting the product surface at the end of the frying. Indeed, when the fried product is removed from the fryer a layer of oil remains adhered at the surface of product and can penetrate into the product pores.

During frying period, the textural properties of the surface of the product influences initial wetting and capillary absorption, but water evaporation limits significant absorption. During this period, the moisture inside the food is converted to vapor, causing a pressure gradient. The vapor tends to escape through capillaries and channels in the cellular structure. The oil that adhered to the surface of product or absorbed is pushed out. The movement of steam out prevents the oil to be absorbed. As long as steam is generated during food frying, oil uptake movement can be described as an advance and retreat process (Dana & Saguy, 2001). These observations were confirmed by Vitrac *et al*. (2000) who measured the internal pressure within a model starch material during frying and during cooling. An overpressure (P_v-P_{atm} in Eq. 1) of 45 kPa inside the food was assessed during frying and prevented any migration of oil inside the material. However, during cooling, oil penetration is no longer affected by this mechanism and occurs by the capillary action. In addition, the rapid temperature decrease in crust (as hygroscopic domain) generates an immediate condensation of steam which is responsible of pressure drop down and oil absorption. Recently, we have studied the mechanisms by which the oil is absorbed by the product (Ziaiifar *et al*., 2008).

The mechanism of oil uptake is complex and affected by numerous factors, such as product and oil composition (Dana & Saguy, 2006). Moreira & Barrufet (1998) and Bouchon & Pyle (2005) have studied the equations by which the oil is absorbed into the pores of product during cooling period. Bouchon & Pyle (2005) took into account the condensation of steam as an additional driving force. They stated that oil uptake happens by positive or negative effects of several elements: surrounding air pressure, vapor pressure inside the product, capillary pressure, and gravity pressure, as:

Eq. 1. $$Q = \frac{\pi r^4 \left[\left(\frac{2\sigma_{\mathrm{lg}} \cos\theta}{r} - (P_v - P_{atm}) \pm \rho g h \cos\alpha \right) \right]}{8\mu l}$$ From Bouchon & Pyle (2005)

where, Q is volumetric flow ($m^3 s^{-1}$)*, r the pore radius (m),* σ_{lg} *interfacial tension between the oil and air* ($N.m^{-1}$)*, θ the wetting angle between the oil and the solid (rad), and* ρ *is the oil density* ($kg.m^{-3}$)*, g the acceleration gravity* ($m.s^{-2}$)*,* P_v *vapour pressure inside the pore (Pa),* P_{atm} *surrounding air pressure (Pa), μ is the oil viscosity (Pa.s) and l oil penetration distance (m).*

This equation combines both Darcy and Washburn equations which relate the flow rate to the piezometric pressure drop within a tube of circular cross section, assuming laminar, steady and fully developed flow.

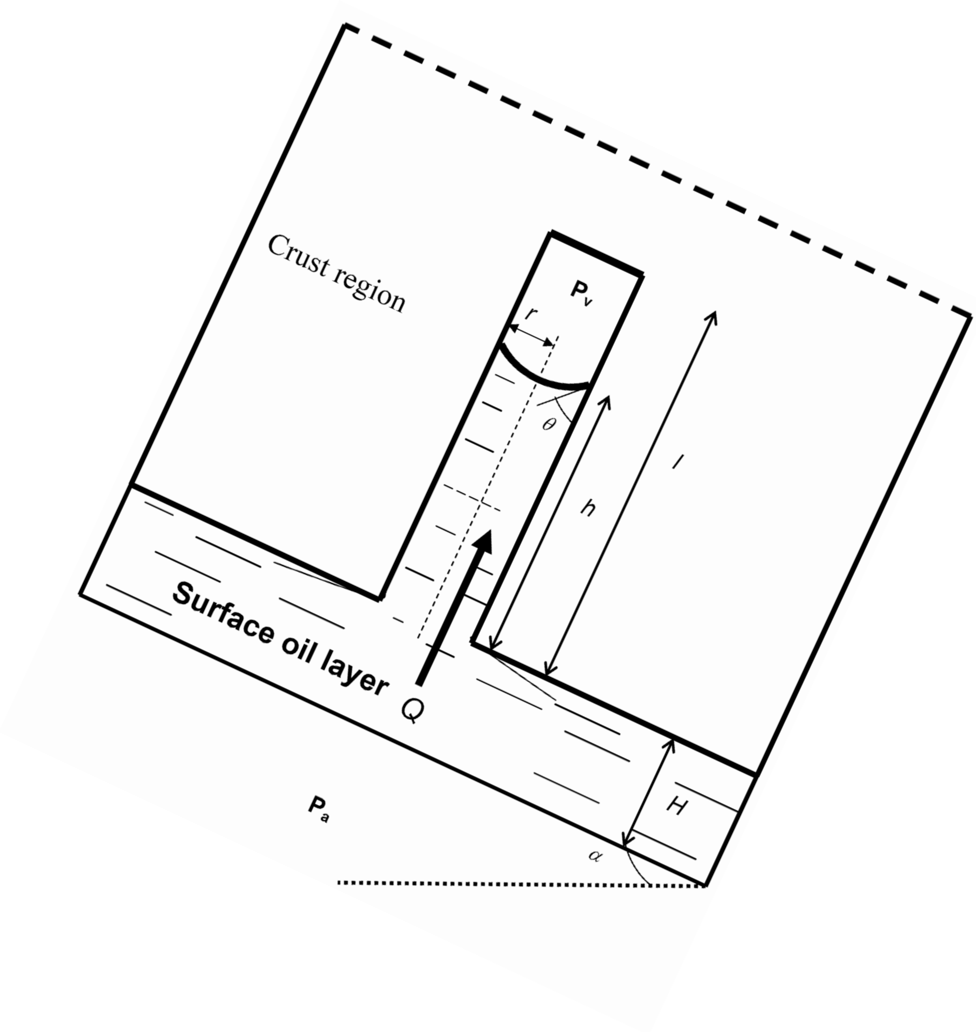

Figure 1. The oil penetration into the porous product during cooling period (According to Moreira et al., 1997, Bouchon & Pyle, 2005 and Ziaiifar et al., 2008).

The temperature is the main factor influencing the cooling condition and oil absorption. Indeed, the physical properties of oil and product such as the oil viscosity, oil density, interfacial tension (between oil and product) and vapor pressure in the food material, which play roles in oil absorption, all, are influenced by temperature. Several authors have studied the variation of product temperature during frying process. Farid & Chen (1998) studied the product centre temperature during frying. They found that product center temperature increases until it reaches the water evaporation temperature, and then it remains unchanged. Califano and Calvelo (1991) stated that oil temperature had no effect on heating rate (conductive coefficient) at the centre of a potato during frying. Later this fact was explained by Farkas *et al.* (1996) by introducing the presence of a moving crust/core interface (evaporation front) in their model. Pravisani and Calvelo (1986) observed that the temperature inside the sample is slightly higher than water evaporation temperature and tends towards 103°C. The reason for this behavior is the liquid present in material is a solution of water and solutes which has higher boiling temperature than the water. Whereas many studies were performed to investigate the center temperature, few studies (Moreira & Barrufet, 1998; Bouchon & Pyle, 2005) measured the temperature of the part of product where oil uptake takes place.

Interfacial tension, which is influenced by temperature, measures the degree of interaction between the oil and the food material. An increase in interfacial tension leads to an increase in oil uptake (Ziaiifar *et al.*, 2008). Therefore, the ability to control the level of oil interfacial tension can greatly enhance the quality of the fried product. Surfactants are chemical compounds such as soaps, phospholipids, inorganic salts and polymers. They increase the interaction between oil and water. As the oil degrades, more surfactants are formed, causing increased contact between the food and oil. This causes excessive oil uptake by the food and an increased rate of heat transfer to the surface of the food (Blumenthal & Stier, 1991; Pinthus & Saguy, 1994; Stier, 2004).

The wettability of a liquid on a solid surface is expressed by the contact angle between the liquid and the solid. When the contact angle approaches the zero value, the liquid spreads over the solid, wetting it; alternatively, for a value higher than 90° the liquid does not wet the solid and does not enter capillary pores. Rossi *et al.* (2008) stated that the contact angle is an index for oil uptake. They have found a significant correlation between contact angle and potato oil uptake when frying performed with sunflower oil. For a system in equilibrium state the interfacial tension and contact angle are related by Young's equation as:

Eq. 2. $$\sigma_{\mathrm{lg}} \cos(\theta) = \sigma_{sg} - \sigma_{sl}$$

where: σ_{lg} interfacial tension between liquid and gas (N/m); θ contact angle; σ_{sg} interfacial tension between solid and gas (N/m) and σ_{sl} interfacial tension between solid and liquid (N/m).

This equation shows that oil absorption is facilitated by the reduction of the interfacial tension between food and oil. Pinthus and Saguy (1994) found a power relationship between the initial interfacial tension and oil uptake, and a linear relationship between oil uptake and contact angle.

The oil viscosity is the one of most important factors in heat and mass transfer phenomena during frying. During deep fat frying, the oil viscosity changes considerably with frying temperature. This change must be taken into consideration when designing frying operations so that product quality can be controlled. Viscosity of oil is strongly affected by its degradation products, increasing as a result of formation of dimers, trimers, polymers, epoxides, alcohols and hydrocarbons, all of which contribute to the increase in viscosity (Stevenson *et al*., 1984). In fact the formation of high-molecular-weight compounds via carbon- to-carbon and/or carbon-to-oxygen-to-carbon bridges between fatty acids is the main factor in the oil viscosity increase (Maskan, 2003). Oil viscosity determines the thickness of adhered oil at the surface of fried product; the higher viscosity the thicker the adhered oil layer and lessen oil drainage when the product is removed from fryer (Ziaiifar *et al*., 2008). On the other hand, it determines the oil flow into the product during cooling period (eq. 1). Therefore, the oil viscosity plays a contradictory role in oil absorption.

Several methods were proposed to diminish the oil absorption during cooling period. Hot air impinging is one of them. This method maintains the product temperature and prevent cooling, thus partially preventing the steam condensation and vacuum effect in oil absorption (Dana & Saguy, 2001). Other methods such as centrifugal force (used in small scale) and high steam velocity treatment were also reported in previous studies (Banks, 1996).

As the oil absorption takes place from the superficial adhered oil layer into the fried product, it is interesting to investigate the physical properties of this oil. The objective of this study at first is to investigate the variation of adhered oil temperature and to find the relation between these variations with the oil physical properties which are important in oil absorption. In the second part of this paper, different conditions of cooling period were carried out to investigate the effect of these conditions on oil uptake of fried product.

2. Materials and methods

2.1. Frying

Potatoes (Bintje variety) and sunflower oil were the raw materials. Potato tubers were stored at 4°C and 95% relative humidity. The potatoes were cut into 8×8×60 mm^3 rectangular pieces and samples with the same mass (app. 5 g) were selected. The samples were washed in distilled water and excess surface water was removed using tissue paper. A domestic deep fat fryer with temperature control of ± *1°C* (Seb, France) was used for carrying out frying operations. Fryer capacity was 4 *l*. The fryer was filled with sunflower oil. The potato to oil ratio was kept at 1:100 w/v to reduce temperature variation in the oil bath. The samples were placed in a metal mesh basket and a complementary cover was installed above the basket ensuring immersion frying and preventing samples from floating. The frying was performed at 170°C. After each frying experiment, the level of oil was checked and the frying oil was changed after 10 h of frying time. All experiments were performed in triplicate and the present results are the mean of the obtained values. The error bars represent standard deviation over the triplicates.

2.2. Cooling

As cooling period is known a curious period in oil absorption, the sample cooling was carried out in different conditions immediately (some seconds) when the product is removed from fryer:

- Cooling at ambient temperature (20°C) and atmospheric pressure (reference condition)
- Reference condition + surface oil was removed by paper
- Reference condition + surface oil was washed by petroleum ether for 1s (Method used by Moreira *et al.*, 1997).
- Cooling at ambient temperature and a reduced pressure (300 mbar). Vacuum cooling was performed using an enclosed chamber. Additional pump was installed to operate at low pressure.
- Reference condition + centrifuged at 600 rpm for 4 min.
- Reference condition + centrifuged at 1200 rpm for 4 min

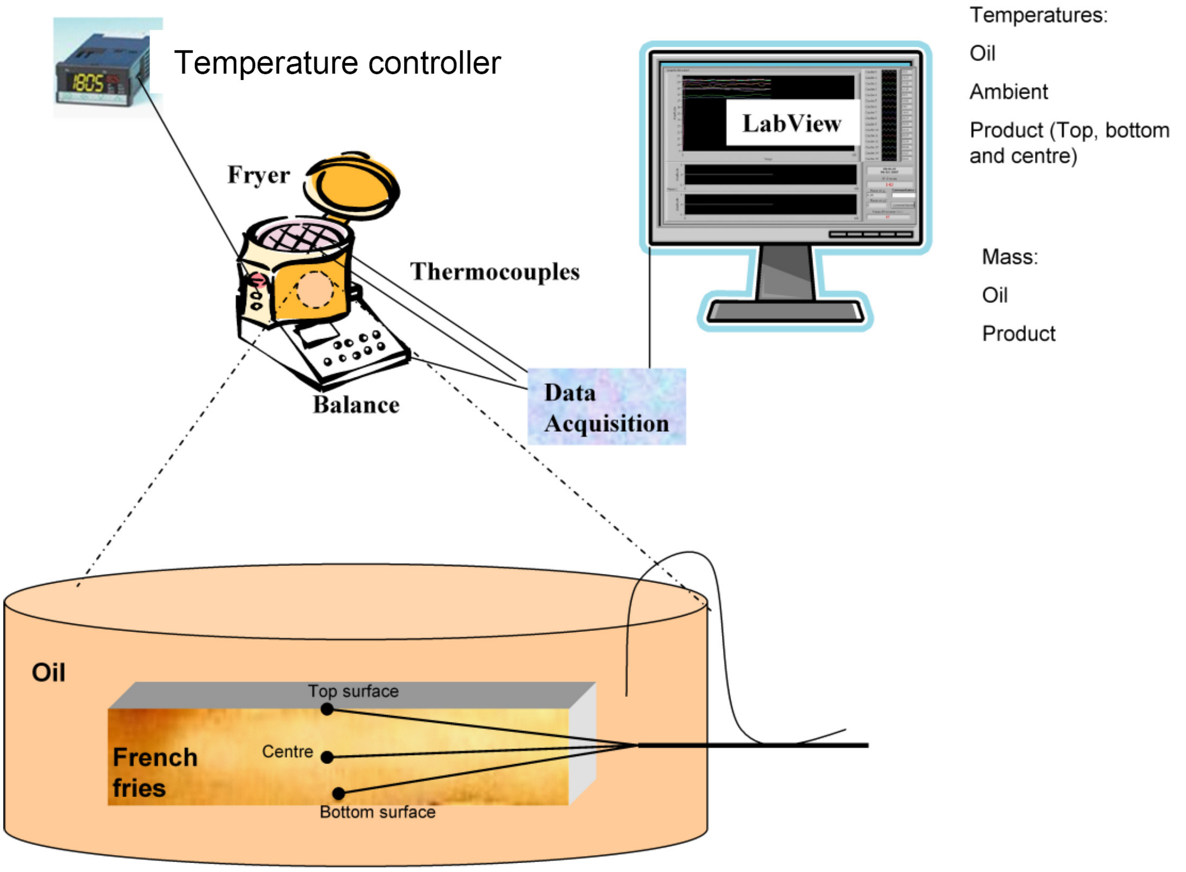

Figure 2. Data collection of temperatures and mass during frying.

2.3. Analysis

Oil content was measured using this Soxhlet method. Temperatures (oil and product) data were collected using the data acquisition system (LabView®; f=1Hz). T type thermocouples (copper-nickel) with accuracy of ±0.1°C were used to measure the temperatures. Temperature acquisition TC-08, Pico® (Technology Limited, England) with accuracy ±0.5°C and temperature controller PID Rex- D-100® (RKC) were used to data collection and oil temperature control, respectively. In the crust region where large temperature gradients exist, a small- shift in thermocouple position will lead to large changes in temperature. So, special care was taken to measure the right temperature.

The Brookfield viscometer was used to measure oil viscosity at different temperature and at a given shear rate of 350 sec^{-1}. The viscous drag of the fluid against the spindle is measured by the spring deflection and measured with a rotary transducer. The oil density was measured using a glass pycnometer (approximately 28 mL).

3. Results and discussions

3.1. Product temperature during frying and cooling periods

Figure 3(a, b) shows the temperature in different position of product i.e. the center, 1 *mm* under surface and at the surface during frying and cooling period. These curves exhibit classical features observed many times in previous studies (Farid and Chen, 1998; Achir, 2007). In our experiments, frying was stopped when water evaporation was still vigorous enough to prevent oil penetration. Surface temperature closely follows that of the oil; however, the center temperature of the fried product does not exceed 100°C. In agreement with the finding of Califano and Calvelo (1991) and Yildiz *et al.* (2007), the center temperature reaches about 100°C (water evaporation temperature) and then it remains constant during frying period. The temperature under 1 mm from the surface of French fries reaches rapidly 100°C and after a small time of being in 100°C it tends to increase constantly.

As oil absorption takes place during cooling period, it is useful to focus on the temperatures in this period. As shown in Figure 3b, during the first 20 s of cooling, all temperatures are well above the boiling temperature and then they approach the ambient temperature. This fact agrees the results of Moreira *et al*. (1997) who stated that the oil absorption takes place during this period while the surface temperature is still greater or equal to the evaporation temperature. This fact suggests that the governing mechanism for oil uptake can be the capillary rise. Another possible mechanism for oil absorption, as highlighted by Bouchon and Pyle (2005), is steam condensation and vacuum effect. While Moreira *et al*. (1997) stated that when the product temperature is above the water boiling temperature, no steam condensation can occur (while oil is absorbing). They neglected the effect of steam condensation and vacuum effect in oil absorption.

In literature, there is lack of information about the steam condensation temperature at the surface of fried product which depends to water activity. The pores allow capillary condensation to occur at a critical water activity (Bassal *et al.*, 1993). Capillary condensation can be described as the process by which surface tension effects cause the direct condensation of moisture in the pores or “capillaries”.

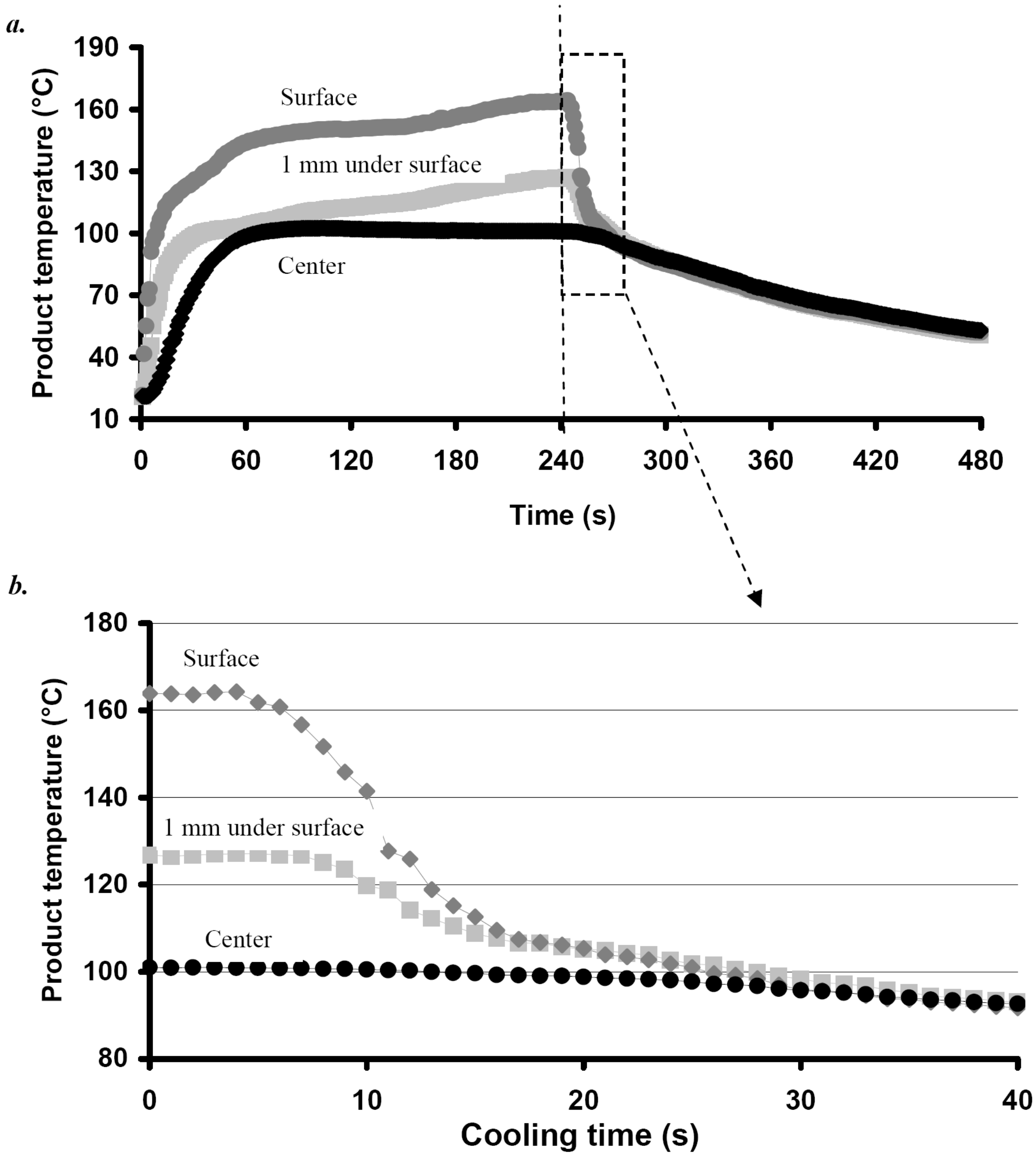

Figure 3. Temperature at different locations within the product during frying process (T_{frying} =185°C, $T_{cooling}$=20°C) a. whole process (frying and cooling) b. cooling period.

3.2. The physical properties being important in oil absorption and influenced by temperature

3.2.1. Oil interfacial tension

Figure 4 shows the experimental results of Moreira *et al.* (1997) on interfacial tension between oil and air. The interfacial tension increases when oil cools, increasing the oil uptake flow according to equation 1. This interfacial tension data cannot be used in modeling of oil absorption during cooling period. Because the product pore are filled with water vapor and not with air which escaped before from the product during frying period. Therefore, it is interesting to measure the interfacial tension between oil and water vapor in order to obtain more meaningful data in future model simulations of oil absorption phenomena.

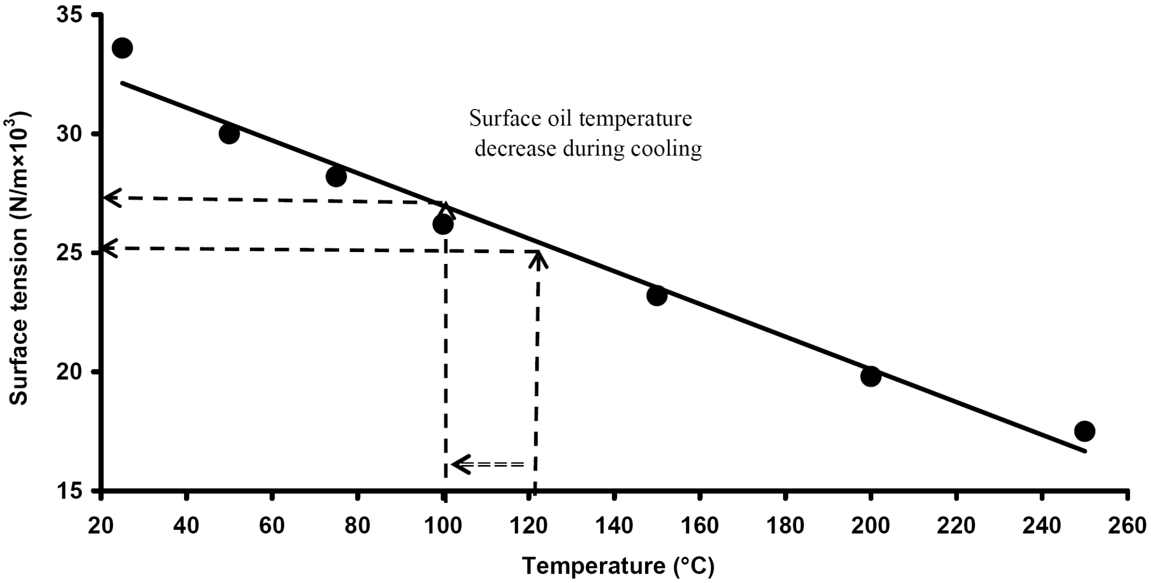

Figure 4. Interfacial tension between soybean oil and air as a function of oil temperature decreasing during cooling (According to Data from Moreira & Barrufet, 1998)

3.2.2. Oil viscosity

The frying oils are Newtonian liquids in usual frying conditions having high viscosity due to their long chain structure. The role of viscous forces is observed by comparing the oil uptake of chips fried in palm oil (melting point about 30°C) and cotton seed oil (melting point about

7°C). Palm oil, which solidifies rapidly during cooling, leads to a high surface adhesion and a low penetration depth, whereas cotton seed oil penetrates deeply inside the product (Vitrac *et al*., 2002). This point is arguable because as shown in figure 3 the oil absorption occurs when the oil temperature is well above the oil melting point. Figure 5 shows the variation of sunflower oil viscosity as a function of temperature. In the temperatures range in which the oil uptake takes place (between about 120°C and 100°C) there is no visible decrease in viscosity. The viscosity remains unchanged approximately at 23 mP.s at this range of oil temperature. Therefore, the oil viscosity can be taken in account as unchanged factor in the modeling of oil absorption during fring period and also during early stage of cooling period. There is also no significant viscosity difference between used oil (20h of heating) and fresh oil during frying at the temperatures higher than 25°C. Whereas, below 25°C, the used oil viscosity is higher than fresh oil and its crystallization temperature is slightly higher than fresh oil (8°C to 6°C). This fact can be seen in figure 5 with a sharp increase in viscosity at these temperatures. A high oil viscosity and/or the use of hard fats will lead to less easy drainage of oil when the fried food is removed from the fryer. Higher viscosity leads to higher oil absorption. Therefore, it will be of interest to conduct a study in order to decrease the oil viscosity.

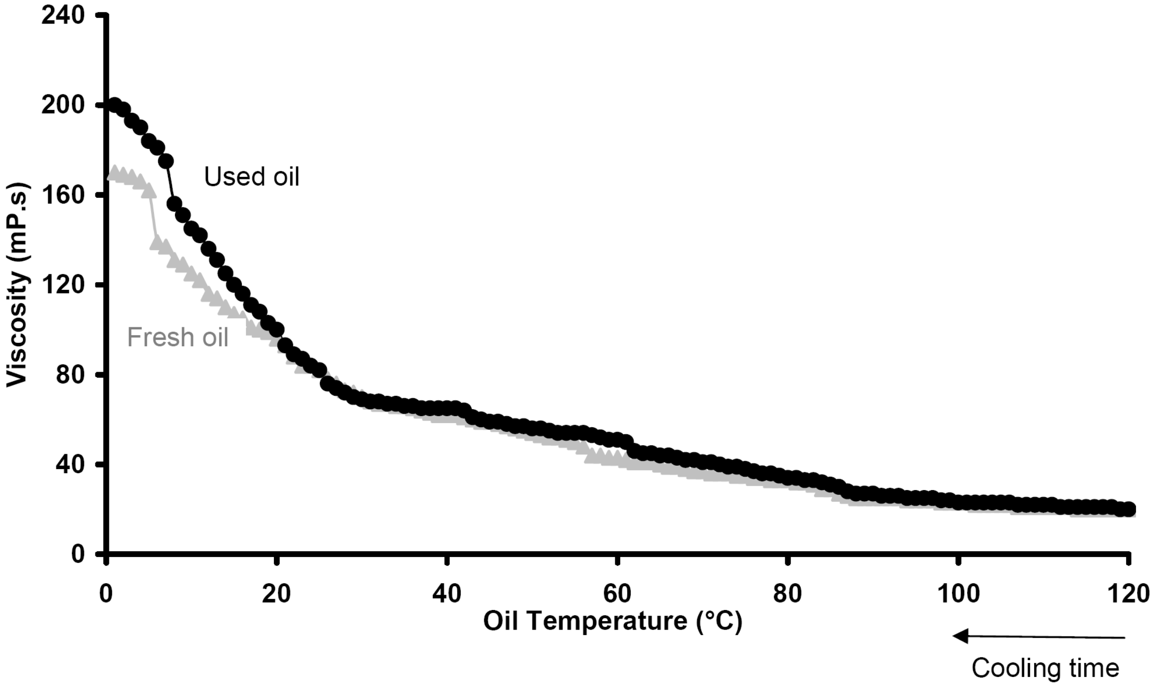

Figure 5. Sunflower oil viscosity as a function of temperature (shear rate =350)

3.2.3. Oil density

The effect of oil density can be positive or negative depending on the position of oil at the top of product or under it. For the oil adhered under the product, the action of gravity (which is calculated from the density) restricts capillary penetration and vice versa (Figure 2). Figure 6 illustrates the variation of oil density as a function of frying oil temperature. The oil density decreases when the oil temperature is increasing. Ziaiifar *et al.* (2008) stated that the oil density is very small when compared with capillary pressure and vacuum effect.

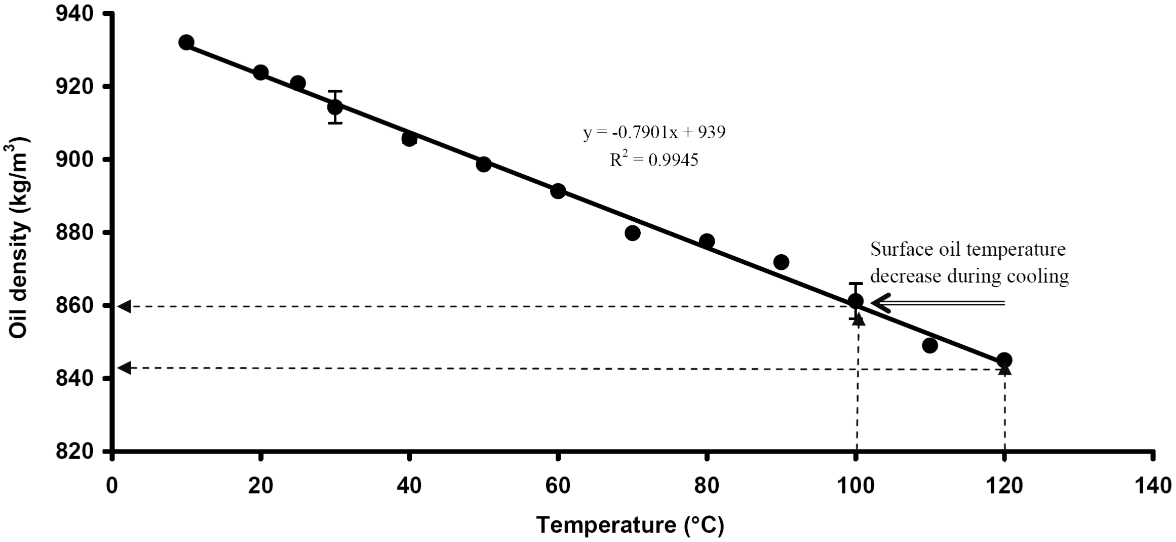

Figure 6. Density variation of Sunflower oil as a function of oil temperature

3.2.4. Discussion

Oil absorption is related to different pressures during cooling period (eq. 1). The two important phenomena in oil absorption are capillary pressure and vacuum effect which is related to water vapor condensation in the product. Therefore, the oil absorption results from a balance of these two pressures. In order to limit the oil absorption it is interesting to find the condition in which the difference of vapor pressure inside the product and surrounding cooling air temperature (Pv-Patm) is higher than capillary pressure i.e.:

Eq. 2. $P_{cap} < (P_v - P_{atm})$ where $P_{cap} = \dfrac{2\sigma \cos\theta}{r}$

3.3. Some experimental works to reduce oil absorption during cooling period

Figure 7 shows the oil content of fried product after being cooled in different conditions. Results showed that the oil content was 0.30, 0.28, 0.27, 018, 0.08, and 0.06 for the samples cooled at reference condition, surface oil removal by paper (6% less oil content when compared with reference condition), at vacuum condition (10%), centrifuged at 600 rpm for 4 min at 20 °C (43%) surface oil washing by petroleum ether (73%), and centrifuged at 1200 rpm for 4 min at 20 °C (80%), respectively. The mechanisms or affecting factors responsible to oil reduction in these conditions were discussed as follows for each case.

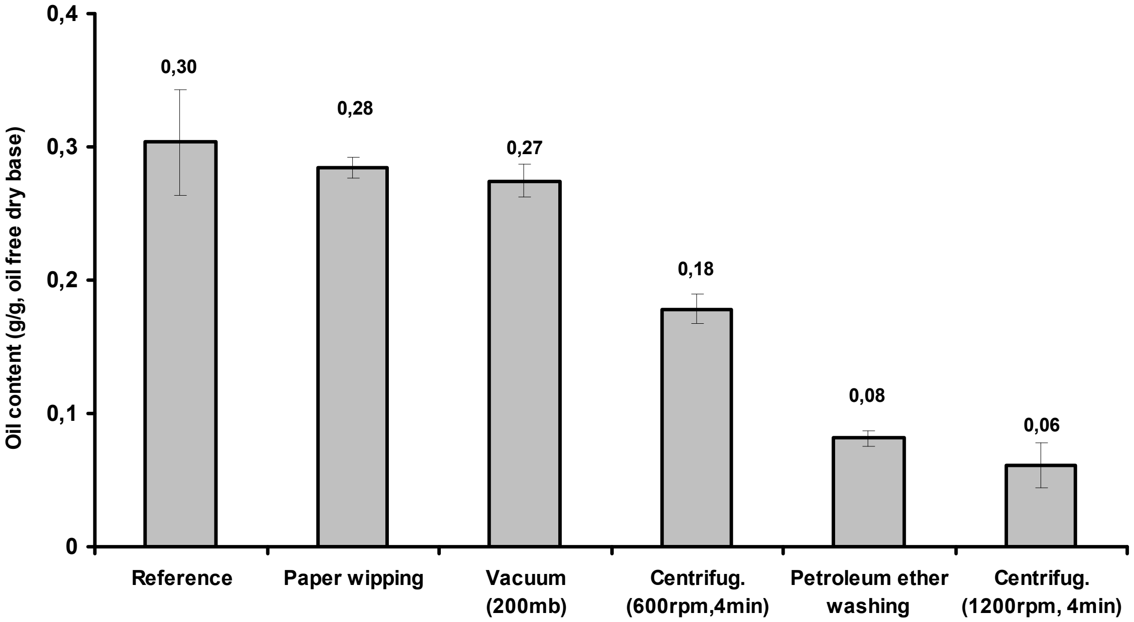

Figure 7. Oil content of French fries cooled in different conditions (frying was performed at 170°C for 4 min for all samples)

3.4.1. Reference condition

This condition is a reference condition which exists in both industrial and home frying. In this condition, the product cools at the ambient temperature and atmospheric pressure.

3.4.2. Reference condition + surface oil removed by paper

In the works of Patterson *et al*. (2004) and Dincer & Yildiz (1996), after frying the product is removed to drain on absorbent paper towel. This is a delicate work because the towel absorbs "the unabsorbed surface oil". As shown by Moreira at al. (1997), the oil absorption takes place mainly during 20 first seconds of cooling period. This was the motive to test the effect of absorbent paper in final oil content of product. Dana & Saguy (2001) stated that simply wiping with an absorbent paper can reduce oil uptake up to 35%, depending on the surface area of the product. This method is not applicable in food industry. In addition, the accuracy of this method is arguable since the ability of paper in oil removal is not measurable. Using this method, the surface oil which is not still absorbed by the samples is partly absorbed by the paper. This situation decreases the thickness of oil adhered to the surface of samples. As shown in Figure 7 in French fries only 6% oil content reduction was achieved by this method.

3.4.3. Reference condition + surface oil was washed by petroleum ether for 1s

The reason for using petroleum washing was to eliminate the adhered surface oil which was not yet absorbed but could be absorbed during cooling by product. This method eliminates totally the unabsorbed oil which is adhered to the product. In this situation, no oil absorption takes place during cooling period. Therefore, the oil content is limited to oil which is initially absorbed by the samples when they in hot oil. This method decreases considerably oil content by 73%. This method cannot be used in the preparation of fried product due to the health risks related to the petroleum ether.

3.4.4. Cooling at ambient temperature and reduced pressure (200 mb)

Vacuum cooling is a rapid evaporative cooling technique that can be applied to various food products. The principle is that by reducing the pressure, evaporation of water is accelerated. The heat for evaporation is removed from the product, causing it to cool. The effect of this method on oil content is not considerable: only 10 % reduction in oil content. The oil reduction using vacuum cooling can be explained by non-stop water evaporation during the early stage of cooling which causes more oil drainage from the surface of product. Furthermore, in vacuum cooling, Pv-Pa is higher than in atmospheric pressure, limiting the oil absorption.

3.4.5. Reference condition + centrifuged 600 rpm, 4 min

The sample centrifugation was performed after 1 min of cooling period where the surface oil was ever absorbed. The centrifugation discharges the absorbed oil from the product. By the rotation rate of 600 rpm 43% of oil was removed compared to reference.

3.4.6. Reference condition + centrifuged 1200 rpm, 4 min

The higher rotation rates of centrifuge, the more oil emptying from the product. The oil content was considerably decreased (80%) by this speed of rotation. The disadvantage of this method is related to the structural deformation of product. In this case the crust was ripped out resulting in non-acceptable visual properties.

4. Conclusions

The oil absorption is a result of complex phenomena which take place during frying process, especially during cooling period. The surface oil temperature which varies according to cooling condition is determining factor in oil absorption. It influences the oil physical properties which are important in oil uptake such as interfacial tension, viscosity and density. During cooling period, when the surface oil temperature tends to decrease, the oil interfacial tension and viscosity increases, resulting in more oil absorption of product. While, the oil density decreases results in positive or negative effect on oil absorption depending on the position of adhered oil on the product. Some processes can reduce oil uptake during cooling period. Several methods were proposed in order to decrease the oil content of product. It was found that the oil washing by a solvent and using the centrifugation decreased considerably the oil content of fried product, while the vacuum cooling and oil removing by the paper were low effective. In conclusion, the combination of these methods, especially centrifugation in vacuum condition can be more effective to decrease the oil content of fried product. Adding a period between frying and cooling, in which the temperature of surrounding air is maintained higher than boiling temperature can eliminate the effect of vapor condensation and decrease oil content.

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CONNECTING TEXT

The experimental studies of the last part were performed in order to collect meaningful data for the thermal conductivity of fried potato, investigated in crust and core region. The previous studies about the thermal conductivity of fried foods were limited to the whole product while the fried product has two distinct regions: crust and core. In this part, the crust regions were carefully removed from the core region and the thermal conductivity were measured in these regions. In addition, some phsysico-chemical reactions such as dehydration and starch gelatinization which take place during frying can change the thermal conductivity of fried products.

To measure the thermal conductivity a modified Lees method was used. This method which was recently modified by Heyd et al. (2007) has some advantages when compared with other methods. This method works in symmetric condition and a fan is used in order to have a homogenous convection in the system. In addition, it is more appropriate to measure the thermal conductivity in the thin and low conductive crust layer.

Part 3: Investigation of effective thermal conductivity kinetics of crust and core regions of potato during deep fat frying using modified Lees method

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Abstract

The knowledge of the value of thermal conductivity of different regions in fried products is needed for mathematical modeling of frying process. While thermal properties of fresh and fried foods are well documented in the literature, thermal properties of crust and core regions are not available. In this study, the effective thermal conductivity of potato, in crust and core regions, during deep-fat frying was investigated. The variation of some characteristics of crust and core in relation to frying time was discussed. The fried product has a porous structure especially in crust region. An improved Lees apparatus, in which the sample is enclosed between the plates, was successfully used to directly determine the effective thermal conductivity of porous samples. The potato were cut in a dimension of $0.05 \times 0.05 \times 0.006$ m^3 *and fried for 1-10 min at 170°C. Top and bottom crusts were separated from core region after each frying time and their thermal conductivities were individually measured. Results showed that the core effective thermal conductivity (k) increases with frying time reaching a maximum value of 0.6 W/(m.K) at 3 min of frying and then decreases to 0.4 W/(m.K) at the end of frying. This behavior can be related to physico-chemical changes such as starch gelatinization and moisture loss in the core region. Top and bottom crust thermal conductivities decrease with frying time due to moisture loss and formation of a porous structure.*

Keywords: Thermal conductivity, frying, crust, core, starch gelatinization

1. Introduction

Deep-fat frying is widely used in industrial or institutional preparation of foods (Pinthus *et al.*, 1993). It is a complex process due to strong couplings between heat and mass transfers (Datta, 2007). Heat is transferred from oil to food material by convection at the surface and conduction throughout the product. Product thermal properties are necessary to be determined with the study of heat transfer during processing; they are also needed to perform mathematical modeling and computer simulation. Among the physical properties, thermal conductivity (k) is one of the most critical (Donsi *et al.*, 1996), because it determines the rate of heat transfer within the product. Thermal conductivities of food materials vary between that of water (k_{water} = 0.614 *W/(m.K) a*t 27°C) and that of air (k_{air} = 0.026 *W/(m.K) a*t 27°C), which are the most and the least conductive components in foods, respectively (Sahin & Sumnu, 2006). Several authors have studied the thermal conductivity of food materials during thermal dehydration process. They have shown a decrease in thermal conductivity with process time and temperature. In most cases, they have related this decrease to moisture loss (Rice *et al.*, 1988; Wang & Brennan, 1992; Donsi *et al.*, 1996; Sablani & Rahman, 2003; Muramastu *et al.*, 2007).

Table 1. Thermal conductivity of some food materials in literature

Product	Moisture content (X, w.b. %)	Temperature (T, °C)	Equation (Mathematical or experimental)	Thermal conductivity (W/(m.K))	Method used	References
Potato	80	50-100	$k=a_1+a_2T+a_3T^2$	0.545-0.957	By measuring the center temperature	*Califano & Calvelo (1991)*
Potato	0-82	40-70	$k=a+(b \times \log(X))$	0.03-0.5	Heated probe	*Wang & Bernnan (1992)*
Chapati	35-50	> 60	$k = 0.3204 + 0.0091X - 0.008T$	-	Special apparatus using containers	Gupta (1993)
Potato	0-80	Freeze drying	$k=0.389\,X_w+0.1445$	0.2-0.52	Improved Fitch	*Donsi et al. (1996)*
Potato	_	150-190	_	0.38-0.6	Modified Fitch	*Sahin et al. (1999)*
Krostula Dough	36.4	160-190	$k=\frac{W.c_p.(T_f-T_i).\Delta x}{A.\Delta T.\Delta t}$	0.47-0.59	Guarded hot plate apparatus	*Seruga & Budzaki (2005)*

a1, a2, a3, a, b = constants; T=Temperature (°C); K=thermal conductivity (W/mK); *X=moisture content (db);* A=surface area (m^2); C_p=specific thermal capacity (kJ/kg); T_f= final temperature of water for accumulation of energy (°C); T_i= initial temperature of water for accumulation of energy (°C); Δt= time for reaching steady state (h); ΔT= temperature difference between heated and cooled surface (°C); W= mass of water for accumulation of energy (kg); Δx: thickness (m), X_w =Water mass fraction (g/g initial water content).

Table 1 illustrates the presented models for prediction of the thermal conductivity in the literature. Califano & Calvelo (1991) calculated the apparent thermal conductivity by measuring the product center temperature. They showed that during frying the thermal conductivity of potato increases with increase in its temperature. Their results showed that the thermal conductivity increases from 0.55 *W/mK* at a temperature of 50°C to 0.95 *W/mK* at 100°C. Wang & Brennan (1992) correlated a semi-logarithmic equation between thermal conductivity and moisture content during the drying of potato at 40-70°C. Using heated probe method, they showed that thermal conductivity decreases while decreasing in moisture content. Drying in such condition (low air temperature) can only decrease moisture content, while neither starch gelatinizes nor real crust is formed. Using Fitch's unsteady method (Mohsenin, 1980), Donsi *et al.* (1996) measured the thermal conductivity of potato having different moisture content. They stated that thermal conductivity is linearly related to moisture loss. Later, Sahin *et al.* (1999) stated that the thermal conductivity of food materials depends on its porosity, structure and chemical constituents. They showed that the thermal conductivity decreases with increasing frying temperature and its duration due to less moisture content and more oil content. This point is logical because the thermal conductivities of both potato solids and oil are lower than that of water.

In literature, the thermal conductivity has been studied on whole product, while some products (such as potato), when fried, present two regions being different in physical and thermal properties: core being humid and soft and crust having a dry and rigid structure. Crust and core regions of fried products represent different structural properties. Crust formation is the result of changes in the structure of the outer tissue of potato after exposure to hot oil, namely, softening of the middle lamella between cells, starch gelatinization inside cells, and dehydration. Table 2 shows some characteristics of core and crust regions after 4 min at 170°C of frying (Ziaiifar *et al.*, 2008). The crust is partially dehydrated and represents more than 50% of the total initial solid content of the raw potato. Its apparent density is approximately half of core region, while its absolute density is greater than core. The main difference between core and crust is in their porosity; crust is nearly 6 times more porous than core showing its capacity in oil absorption. Therefore, it is expected that the crust and core have different thermal conductivity due to their difference in structure.

Table 2. Some physical characteristics of core and crust (Ziaiifar et al., 2008)

Characteristic\region	**Core**	**Crust**
Moisture content (g/g, db)	3.03 ± 0.13	0.35 ± 0.03
Solid content fraction (%)	42 ± 5	58 ± 10
Apparent density (kg/m^3)	1020 ± 20	580 ± 60
Absolute density (kg/m^3)	1130 ± 10	1430 ± 50
Porosity (%)	10 ± 4	60 ± 5

During frying, the surface of potato heats up to the boiling temperature and water starts to evaporate. As frying progresses, the crust/core interface moves towards the centre of product and the crust becomes thicker and the core decreases in thickness (Farkas *et al*., 1996). Since the intensity of thermal processing varies from the surface region to the interior parts of fried product, it is interesting to measure the thermal conductivities in these different regions. The crust region receives higher energy and it is also the way of leaving vapor. These facts induce a porous structure in this region. In the other hand, the product interior parts (core) are subjected to physico-chemical changes particularly starch gelatinization.

Farid & Chen (1998) used the physical properties of fresh potato and of completely fried chips to represent the properties of the core and crust regions respectively in their model. Assuming constant values for core and crust thermal conductivity can be reasonable when no change takes place in core and crust regions. While during frying, the core starch is gelatinizing and the crust is becoming drier and more porous. On the other hand, the created crusts at the top and bottom of sample are not the same. This point can be concluded from the results of Sahin *et al.* (1999) who experimentally showed that the convective heat transfer coefficient at the bottom surface (120 $W/(m^2 \cdot K)$ is lower than the top surface (320 $W/(m^2 \cdot K)$) due to air and water vapor bubbles entrapped under the food material.

Few studies deal with the thermal conductivity of core and crust regions separately during frying. In addition the effect of starch gelatinization on thermal conductivity has been poorly discussed. The objective of this study is to determine the effective thermal conductivity of potato in three sections: core, top crust and bottom crust as a function of frying time using an improved version of Lees method.

2. Thermal conductivity measurement

2.1. Comparison of different methods

The most commonly used thermal conductivity measurement device for food products is thermal conductivity probe (Rahman, 1995). This method is based on unsteady state heat conduction in the radial direction (Goedeken *et al.,* 1998). In this method, a container is filled with sample and the probe is inserted in the center of the container. The probe is heated at a constant rate. Then, the time versus temperature adjacent to the heat line source is recorded (Sahin & Sumnu, 2006). While being a quick and convenient method, it performs local measurements, and therefore relies on the assumption that the food is homogeneous. If the probe was inserted into a porous texture, such as crust region, the needle might pass through a large air bubble, in which case the measured thermal conductivity would be lower than if the probe were located in a different part of the sample (Carson *et al*., 2004). In addition, the thickness of sample should be large enough to insert the probe inside (Manohar *et al*., 2000). Therefore this method can not be used for the crust regions with 1-2 *mm* thickness. The method described in this paper does not suffer from these problems, since its measurement is based on heat flow through the entire sample and it can be used for the thin crust regions. Another unsteady state thermal conductivity measurement method is Fitch apparatus. The Fitch method consists of a heat source (a vessel filled with constant temperature liquid) and a copper plug insulated on all sides except the face in contact with sample. The sample is sandwiched between the heat source and the copper plug. The temperature of the plug varies with time depending on the heat flow rate through the sample (Sahin & Sumnu, 2006). For the heat storage in the sample to be negligible, the sample thickness should be as small as possible. Therefore, the Fitch method does not allow much flexibility in terms of sample size in order to measure a macroscopic thermal conductivity. In addition in this method it is assumed that the heat transfer at the edges of the sample and copper plug is negligible which is arguable. Lees & Schuster (1898) proposed an apparatus to measure macroscopic global thermal conductivity in steady state, in which the sample is enclosed between two plates. The heat power is continuously generated by an electrical resistance and traverses throughout the plates and sample. They assumed that heat convection from plates to air in all surrounding surfaces is uniform; this situation allowed estimating the heat flux. The apparatus was not symmetric from sample’s point of view and cooled by natural convection. Consequently, it makes the hypothesis of uniform heat convection questionable. This situation influences the measurement precision.

2.2. Modified Lees method and its validation

In this study, a modified Lees apparatus (Heyd *et al.*, 2007) which works in symmetric condition was used to measure the effective thermal conductivity of crust and core regions of fried potato (Fig. 1). The advantages of this thermal conductivity measurement procedure include:

- system works in symmetric condition assuring better determination of the heat flux than in the Lees method,
- apparatus is low cost and can be easily implemented and cleaned,
- measurement is performed directly with few hypotheses on thermal properties of apparatus and sample; while non steady state methods require knowledge of the sample’s density and specific heat capacity,
- ability of handling a large range of samples sizes especially thin samples,
- It provides an effective global thermal conductivity measurement rather than a local measurement.

While its disadvantages are:

- Sample should be in slab shape,
- Sample conductivity should be lower than 5 W/mK such that thermal resistance remains much higher than contact thermal resistance between sample and plates.

The sample, enclosed between a hot and a cold plate, is insulated using an adhesive tape on all sides, except two faces in contact with plates, through which heat transfer occurs. Therefore, the convective heat flux dissipated by the sample becomes negligible. The heating resistance supplies a constant small power of 5 W in the hot plate. This power is low in order to minimize the rise of sample temperature. This point is important to avoid moisture loss and product properties changes during tests. In order to facilitate heat transfer (good thermal contact); a little “Jelt Silicone compound” was spread between the cooper plates. The whole apparatus is cooled by forced convection supplied by a fan. Geometrical symmetry and convection type insure the global thermal conductance is the same for the hot and the cold plates. The time to reach the steady state condition was about 40-50 min depending on the sample (crust and core). T-type thermocouples (1 *mm* in diameter) allowed measuring the different temperatures of T_1, T_2, T_3, T_4 and T_{air}. Temperatures were recorded at 10 s intervals using a data acquisition and a switch unit (Agilent 34970A). The computer calculations were performed using SCILAB software. The sample thickness was 1-2 mm for the crust samples and 2-6 mm for the core samples, depending on frying condition.

Fig. 1. The modified Lees apparatus to measure effective thermal conductivity

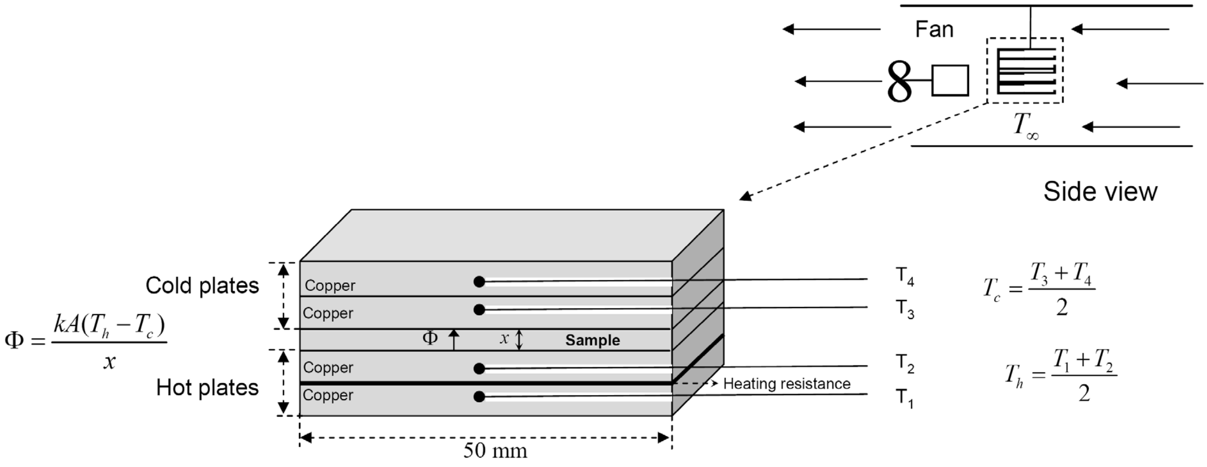


Figure scale 1:1

Since temperature difference between two hot plates and similarly between cold plates is lower than 0.2°C which is negligible when compared with temperature difference between hot and cold plates, it is possible to consider $T_1 \approx T_2$ and $T_3 \approx T_4$, therefore:

$$T_h = \frac{T_1 + T_2}{2} \qquad (1)$$

$$T_c = \frac{T_3 + T_4}{2} \qquad (2)$$

T_h=*Mean hot plates temperature (°C)*

T_c=*Mean cold plates temperature (°C)*

At the steady state there is no accumulation of energy, therefore:

$$P = \Phi_h + \Phi_c = C_h(T_h - T_\infty) + C_c(T_c - T_\infty) \qquad (3)$$

P = Resistance power (W)

Φ_h *= Heat flux dissipated by the hot plates (W)*

Φ_c *= Heat flux dissipated by the cold plates (W)*

C_h *and* C_c*= Global thermal conductance of module with air in hot and cold plates, respectively (W/K)*

T_∞ *= Surrounding air temperature (°C)*

Because of apparatus geometrical symmetry and type of convection:

$$\mathrm{C_h} = \mathrm{C_c} = \frac{P}{T_h + T_c - 2T_\infty} \qquad (4)$$

Heat flux passing through the sample (Φ) is equal to heat dissipated by cold plates (Φ_c), therefore:

$$\Phi = \Phi_c \qquad (5)$$

Finally when the system reaches its steady state, the effective thermal conductivity is estimated by the following equation:

$$kA\frac{T_h - T_c}{x} = C_c(T_c - T_\infty) = \frac{P}{T_h + T_c - 2T_\infty}(T_c - T_\infty) \qquad (6)$$

k= Sample effective thermal conductivity (W/mK)

A= Contact surface area (m^2*)*

x= Sample thickness (m)

$$k = \frac{P(T_c - T_\infty)x}{A(T_h + T_c - 2T_\infty)(T_h - T_c)} \qquad (7)$$

Fig. 2. Typical curves plotted during thermal conductivity measurement

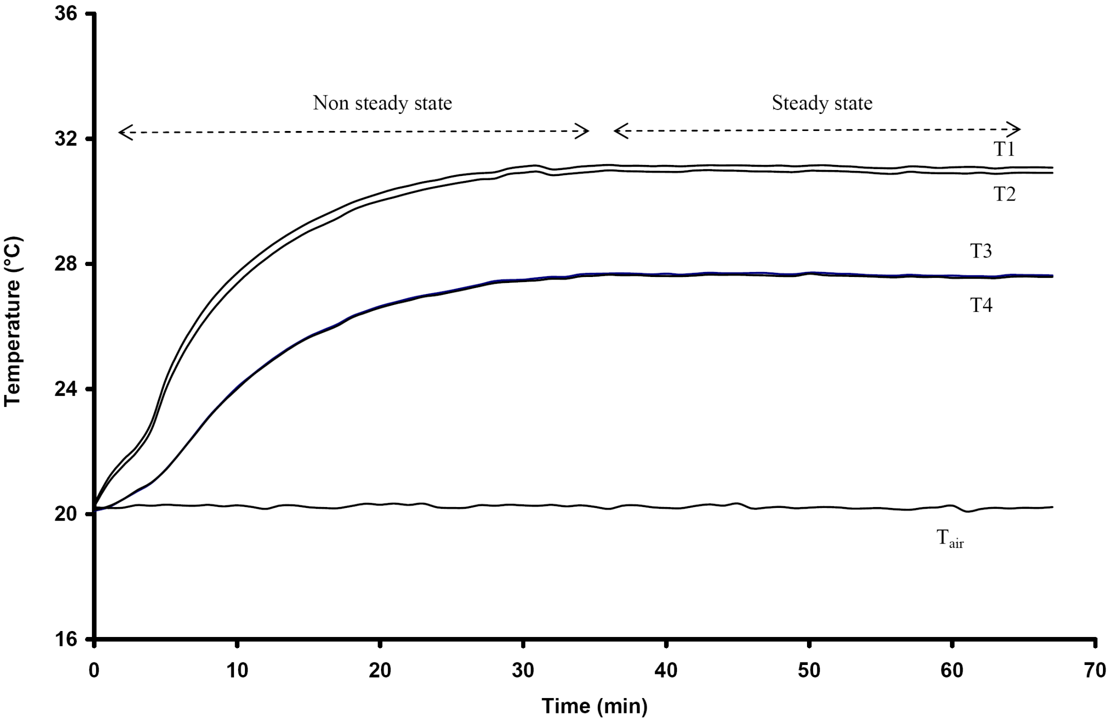


Figure 2 is a typical curves plotted during thermal conductivity measurement. The temperature of hot and cold plates increase and reaches to a constant value. From this point the steady state heat transfer begins during which thermal conductivity was calculated.

In order to validate this method, two materials, one, PTFE (Teflon), with lower thermal conductivity than food materials and another, window glass, with higher thermal conductivity were chosen. In literature, a thermal conductivity of 0.23-0.25 *W/mK* and 0.78-0.81 *W/mK* were reported for Teflon and window glass, respectively (Bejan & Kraus, 2003; Heldman & Singh, 1981). Our results showed that a thermal conductivity of 0.24± 0.01 for Teflon and 0.81± 0.01 for window glass which is very close to the data reported in literature.

3. Materials and methods

3.1 Frying and sampling procedure

The potatoes (var. Bintje) with moisture content of about 80% (wet basis) were cut into rectangular slices of $0.05\times0.05\times0.006$ m^3 and samples with same mass were selected. Samples were washed in distillated water to remove surface starch and excess surface water was removed with tissue paper. A domestic deep fat fryer with temperature control of ± 1°C was used. The fryer was filled with 4 *l* sunflower oil. The potato to oil ratio was kept at 1:100 (w/v) to prevent the variation of the temperature in the oil bath. The samples were placed in a metal mesh basket and a complementary cover was installed above the basket ensuring immersion frying and preventing sample from floating. After each frying experiment, the level of oil was checked; frying oil was changed after 10 h of frying time. The frying was performed at the temperature of 170°C. Potatoes slices were removed from the fryer each minute until 6 min and then after 8 and 10 min. It is obvious that the absorbed oil content affects the thermal conductivity. Therefore, in order to eliminate the unabsorbed surface oil, the fried product was shortly emerged in petroleum ether immediately after frying (Moreira *et al.,* 1997; Ziaiifar *et al.,* 2008).

The top and bottom crusts of fried samples were separated carefully from the core by scratching with a scalpel. The crust and core separation is delicate work because the limit between them is not clear, especially at bottom part of product. Therefore, an especial care was taken to remove only the soft layer which did not visually adhere to the crust. The separated parts were sealed in polyethylene film and stored at constant temperature for 24 h to ensure uniform moisture content throughout the sample. All experiments were performed in triplicate and the present results are the mean of the obtained values. The error bars represent standard deviation over the triplicates.

3.2. Analyses

Moisture content was determined by drying the samples down to a constant weight in a convection oven at 105°C. Crust and core thickness were measured using a micrometer. As, the results of the thermal conductivity measured by modified Lees method is sensible to the sample thickness, the measurements were as precise as possible. A Differential Scanning Calorimeter (DSC-7, Perkin Elmer) was used to determine the degree of gelatinization of starch in core region. Samples of 3.5 to 4.0 mg were weighed into aluminum DSC pans. The samples were scanned from 40 to 90°C with a heating rate of 3°C/min. The degree of gelatinization was calculated as follows:

$$\text{Degree of gelatinization (\%)} = \frac{\Delta H_{Raw} - \Delta H_{Fried}}{\Delta H_{Raw}} \times 100 \qquad (8)$$

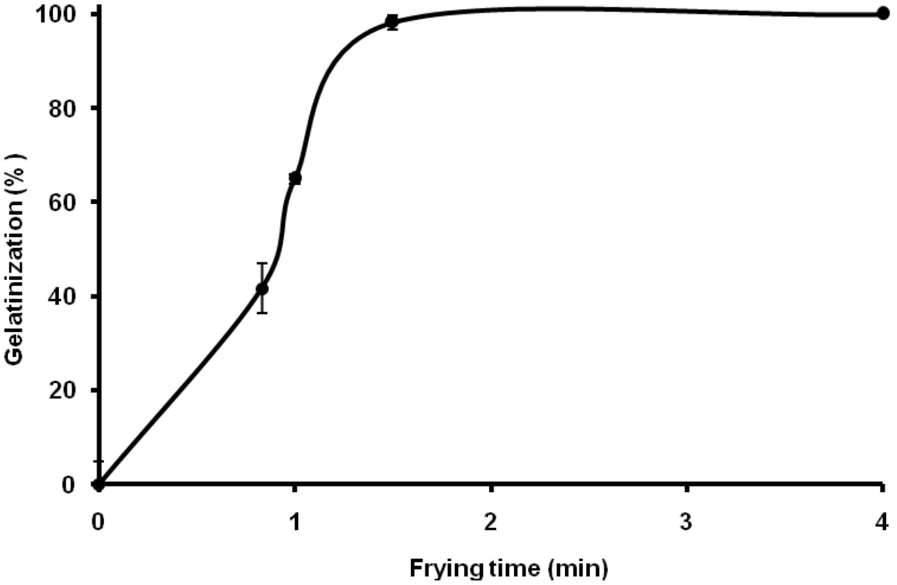
where ΔH_{Raw} and ΔH_{Fried} are enthalpies of the gelatinization for raw potato starch and fried starch, respectively.

4. Results and discussion

4.1. Starch gelatinization

The most important physical change which takes place during frying of potato based product is starch gelatinization. Gelatinization is the major transition of starch during thermal processes. It is the collapse of molecular orders within the starch granule and it causes irreversible changes in starch properties such as granular swelling (Thomas & Atwell, 1999). Achir (2007) stated the core starch gelatinization starts in the early stages of frying, and then starch swelling continues and finalizes by cell separation. These transformations may influence the core thermal conductivity. The starch gelatinization is a rapid phenomenon during frying due to strong thermal processing. Karathanos & Saravacos (1993) stated that during starch gelatinization most of existing pores disappear, decreasing product porosity. The starch gelatinization was very rapid especially in the crust region in which it was completed after 0.5 min of frying (result not shown). As shown in Fig. 3, the core starch was fully gelatinized after frying for 1.5 min.

Fig. 3. Degree of starch gelatinization in centre of potato during frying (measured by DSC method, scanned from 40 to 90°C with a rate of 3°C/min)



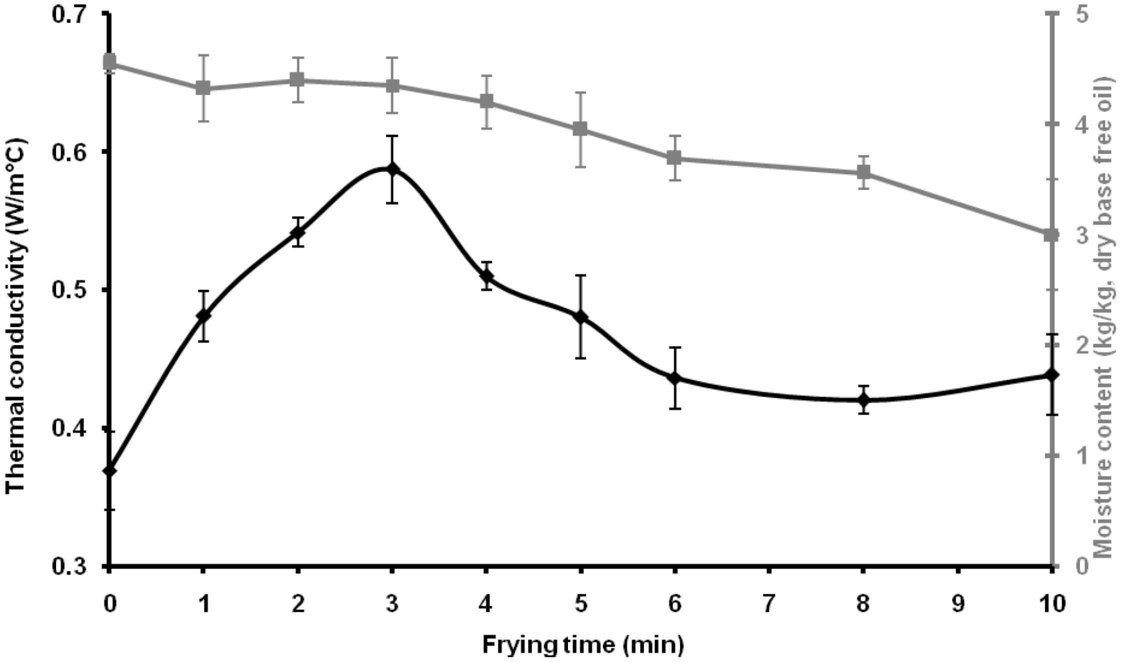
4.2. Thermal conductivity

4.2.1. Core thermal conductivity

Fig. 4 shows the variation of thermal conductivity (k) in core region during frying. The thermal conductivity of core region increases from 0.37 with frying time reaching a maximum value of 0.6 *W/(m.K)* after 3 *min* of frying and then decreases to 0.4 *W/(m.K)*. The thermal conductivity depends to the physical changes in the product during frying.

The changes in core thermal conductivity cannot be related to moisture loss during first 3 min of frying. As shown in Fig. 4, during this stage, no sensible reduction occurs in core moisture content. Therefore, starch gelatinization can be considered as the only affecting factor in thermal conductivity increase in core region during this stage. In this condition, starch is completely swelled causing the air present in the product to be exhausted leading to a subsequent compaction. As air thermal conductivity is low, bringing out the air from product causes higher product thermal conductivity in the product. After 3 min of frying (Fig. 4), the decrease in thermal conductivity can be related to the moisture loss; during this stage the moisture content decreases from 4.35 to 3 (kg/kg, db).

Fig. 4. The thermal conductivity and moisture content of core region during frying



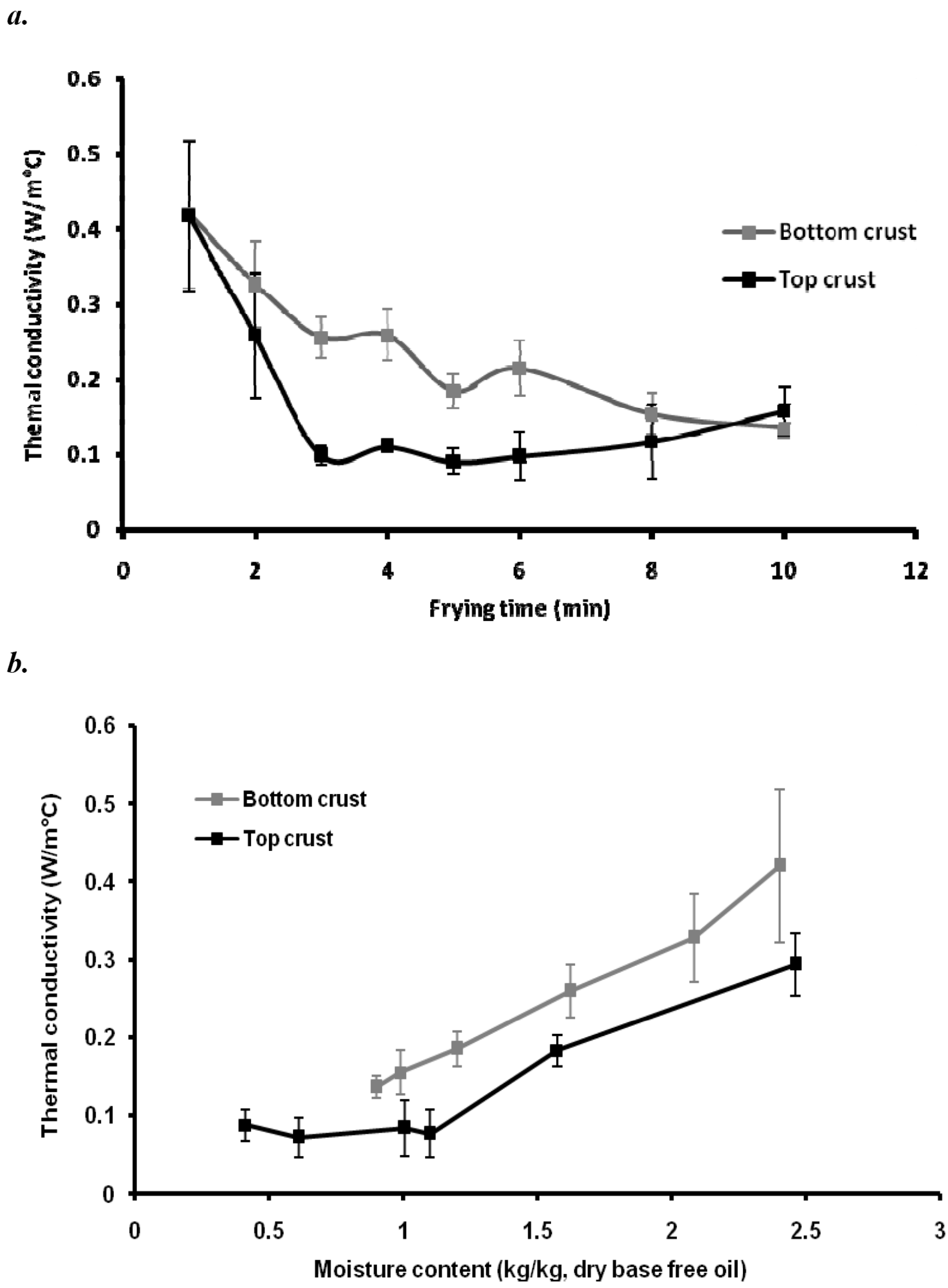
4.2.2. *Crust thermal conductivity*

The effect of thermal conductivity of the crust is very important in frying process since it controls the process. Heat must be conducted through the crust with low thermal conductivity. The crust has thermal properties of an insulating material. Its low thermal conductivity and porosity slow the rate of heat transfer and therefore the rate at which the product cooks and water vaporizes (Chen & Moreira, 1997). Crust presents a dry and porous structure in which the pores are occupied by air. For porous materials, the measured thermal conductivity is an apparent one, called the effective thermal conductivity (k_{eff}). Since it is not possible to measure the thermal conductivity of each composition, an effective thermal conductivity must be used. It is an overall thermal transport property assuming that heat is transferred by conduction through the solid and the porous phase of the material (Sahin & Sumnu, 2006). The modified Lees apparatus, designed in this work, is able to measure such an effective thermal conductivity. In porous crust, thermal conductivity depends on many factors that affect the heat flow paths through the crust, such as void fraction, arrangement of void spaces and homogeneity (Sablani & Rahman, 2003). The crust thermal conductivity is lower than core due this fact that it contains lower moisture content and presents more porous medium when compared with core (Ziaiifar *at al*., 2008). McDonough *et al.* (1993) stated that during frying, surface starch is ungelatinized due to the rapid loss of moisture and increase in temperature. In contrast, Fan *et al.* (1997) stated that the crust starch underwent a rapid gelatinization due to a strong heat transfer. As the evaporation takes place when the surface temperature reached 100°C, it is very likely that the surface starch gelatinizes before water evaporation starts. Arifin (1993) found a thermal conductivity of 0.12 W/m K for the crust with 4.2% (wb) moisture content. Later, a crust thermal conductivity of 0.14 W/m K has been used for modeling in the studies of Farkas *et al.* (1996) and Southern *et al.* (2000). Fig. 5 shows the thermal conductivity of the top and bottom crust as a function of the frying time (4a) and moisture content (4b). In both crusts, the moisture content decreases with frying time. The measurement of moisture content in crust region is difficult due to the fact that the water vapor could condensate in this region in the early stages of cooling. The crust thermal conductivity decreases with decrease in crust moisture content. This result is in agreement with the results of Sablani & Rahman (2003) and Muramastu *et al.* (2007) who have stated that the thermal conductivity of food material is related to moisture content.

As shown in Fig. 5b, in the same moisture content the top crust thermal conductivity is lower than bottom crust. This point can be explained by this fact that top crust is generally separated from core region after certain time of frying due to the water evaporation and represents a net crust (visual observation). While the bottom crust sticks to the core region during frying and may include an intermediate section between crust and core. As the crust thermal conductivity is affected by structural changes, further study especially the changes in its porosity is needed.

Fig. 5. Top and bottom thermal conductivity of crust ***a.*** as a function of frying tim

function of moisture content



5. Conclusions

A modified Lees method was successfully used to measure the effective thermal conductivity in different parts (core and crust) of potato fried at 170°C for 1-10 min. This method was valuable for performing measurements and was more suitable for this purpose than other thermal conductivity measurement methods such as the thermal conductivity probe due to its capacity to measure the effective thermal conductivity of non homogenous materials, easy to use and need to no assumptions on sample thermal properties. There was a need for independent measurements of crust and core thermal conductivity in the fried food since it is the parameter which determines largely the drying rate. The core and crust regions showed different thermal conductivity behaviors. During frying, the core thermal conductivity is influenced by the physico-chemical changes. Starch gelatinization, taking place during the first minutes of frying (3 min), causes an increase in core thermal conductivity; while the moisture loss which starts after 3 min of frying decreases thermal conductivity. The crust thermal conductivity is strongly related to moisture content. The data of crust and core thermal conductivity can help to better understand the frying process and will be used in further work on process modeling.

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Abstract of the thesis

This research was performed to better understand the oil absorption during deep-frying. High oil content in fried products is one of the major issues making them unsuitable for daily consumption. In spite of all research efforts, fried products still contain significant amounts of oil. Experimental studies were performed in order to show by which mechanisms, where and when the oil absorption takes place during frying process. At first, the effect of pore development on the oil uptake was studied. The physical properties of adhered oil at the surface of product on this uptake were then studied. Finally, the effective thermal conductivity of crust and core regions and their effect on heat transfer were investigated. Potatoes were cut into rectangular shapes and fried at different oil temperatures (140, 155, 170, and 185°C). An improved Lees apparatus was successfully used to determine the effective thermal conductivity of fried samples. Results showed that the oil uptake increases as the oil bath temperature decreased from 185 to 140°C. During the frying period, the porosity increases due to forceful water evaporation and pore formation. However, during the cooling period, it starts to decrease as a result of the absorbed oil implanted in the pore spaces and collapse phenomenon. During the cooling period, when the surface oil temperature tends to decrease, the adhered oil interfacial tension and viscosity increase, resulting in more oil absorption. The different regions of product (core and crust) showed different thermal conductivity behaviours. The physico-chemical changes of product which occur during frying influence the thermal conductivity at these regions. In the core region, the starch gelatinization, taking place during the first minutes of frying (3 min), causes an increase in core thermal conductivity; while the moisture loss which starts after 3 min of frying decreases thermal conductivity. In the crust region, the thermal conductivity decreases with frying time due to moisture loss and formation of a porous structure.

Résumé de la thèse

Cette recherche a été menée pour mieux comprendre l'imprégnation en huile pendant la friture profonde. La teneur en matière grasse élevée est un des caractéristiques critiques des produits frits. Malgré des efforts des scientifiques, les produits frits contiennent encore une quantité considérable de matière grasse. De nombreuses études expérimentales ont été réalisées afin de mettre en évidence par quels mécanismes, où et quand l'imprégnation en huile se passe lors du procédé de friture. Dans un premier temps, l'effet du développement des pores sur la prise d'huile a été étudié. L'influence des propriétés physiques de l'huile adhérée en surface du produit sur cette prise a été ensuite examinée. A la fin, les conductivités thermiques effectives des différentes régions du produit (la croûte et le cœur) et leurs effets sur le transfert de chaleur ont été examinées. Les pommes de terre ont été découpées en forme rectangulaire et frites à différentes températures (140, 155, 170 et 185°C). Un appareil de Lees modifié a été utilisé avec succès pour déterminer la conductivité thermique des échantillons frits. Les résultats ont montré que la teneur en huile augmente en diminuant la température de 185 à 140°C. La porosité augmente pendant la friture à cause de l'évaporation forte de l'eau génératrice des pores. Cependant, elle commence à diminuer au cours de la période de refroidissement en raison du remplissage des pores par l'huile et du phénomène de l'effondrement. Au cours de la période de refroidissement, lorsque la température d'huile en surface a tendance à diminuer, la tension interfaciale et la viscosité d'huile augmentent entraînant une teneur en huile plus élevée. Les différentes régions du produit (le cœur et la croûte) ont montré différents comportements au niveau de la conductivité thermiques. Les modifications physico-chimiques du produit qui ont lieu au cours de la friture influent la conductivité thermique de ces régions. Au niveau du cœur, la gélatinisation d'amidon qui a lieu pendant les premières minutes de la friture (3 min), entraîne une augmentation de la conductivité thermique, tandis que la perte en eau qui commence après cette période diminue la conductivité thermique. Au niveau de la croûte, la conductivité thermique diminue avec le temps de la friture en raison de la perte en eau et la formation d'une structure poreuse.