# Theoretical aspects of deep-fat frying

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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.**

***Keywords- frying, modeling, heat transfer, oil absorption***

## I. Introduction

Frying is a very old process that has grown exponentially over the last years. Phenomena occurring during deep fat frying are extraordinarily complex. Frying involves unsteady heat and mass transfer phenomena in porous media (potato can be considered as such), phase change of water, vapor bubble formation and growth on the food surface, natural heat convection in the oil bulk combined with forced heat convection induced by the violent bubble departure from the food surface [4], [21], [29]. According to Farkas *et al.* (1996), deep-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. 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 during deep-fat frying process.

## II. Classification of Frying Models

There are several frying models in literature with different degrees of sophistications. These models can be grouped by different criteria such as:

### A. 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.

#### 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. This type of model was the rule until Farkas et al. (1996) developed a model by considering the two parts of product.

#### 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 [12].

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.

Fig. 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.

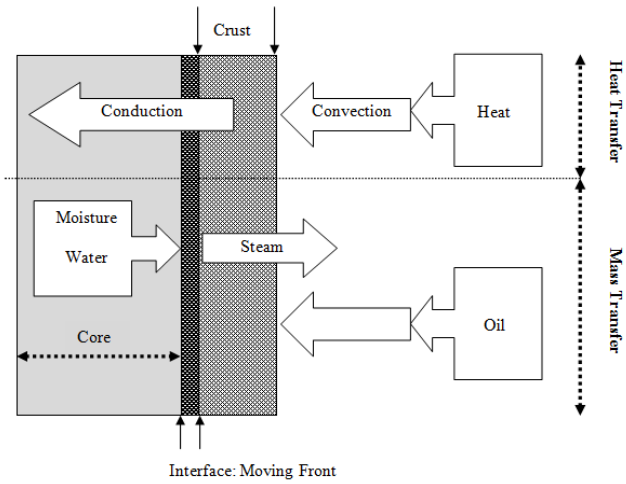


Figure 1. Transfer phenomena (heat and mass transfer) during frying of French fries.

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 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 [12], stated that the neglecting vapor flux in the core and liquid flux in the crust reduced mathematical complications but sacrificed important physics. Lioumbas et al. (2012), examining a crust–core type of model for the simulation of potato frying process , stated that the numerical model developed based on the crust–core approach, is capable to describe the temperature evolution in the potato for all oil temperatures.

### B. *Model types classified by the 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.

#### 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) *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.

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 & Moreira (1997) 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 [3],[32].

### C. *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 behaviors regarding to the physical, structural and thermal properties of food materials.

*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 [14].

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) Mechanistic model*

Mathematical modeling can provide a level of understanding that complements experimentation in ways that are impossible to achieve with experiments alone [14]. 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 modeling 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 modeling process; it can be a powerful tool in predicting certain parameters involved in the frying process.

## III. 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 vapor.

As can be seen in fig. 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.

### A. *Mechanisms of heat transfer*

*1) Heat convention:*

Convective heat transfer coefficient measures the rate of heat transfer from the oil to the food product. Califano & 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 & Singh (1994) concluded that the h value 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 & 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 $W/m^2K$ to 1100 $W/m^2K$ during the frying process.

Many authors take into account that the convective heat transfer coefficient is constant during frying [27],[33]. Some assumed two different values: turbulence convective heat transfer due to bubbling and another one in the absence of bubbling [5],[7],[16]. Use of a constant convective heat and mass transfer coefficient through the process is not reasonable since Hubbard & Farkas (1999) showed through experiments that both heat and mass transfer coefficients vary significantly during different stages of frying and need to include in modeling.

The convective heat transfer coefficients were up to two times higher than those obtained in the absence of vapor 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 $W/m^2K$ in the temperature range of 170- 190°C [22],[31]; while for surface boiling conditions at the initial heating period it is reported to be 800-1000 $W/m^2K$ [13].

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 & Farkas (2000) used a sample heat balance to predict the h value during frying. In agreement with [11], 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 (2005), 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.

*2) Heat conduction:*

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

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

*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 modeling, 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. (2009) studied the heat conductivity in crusts and core (Fig.2). 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.

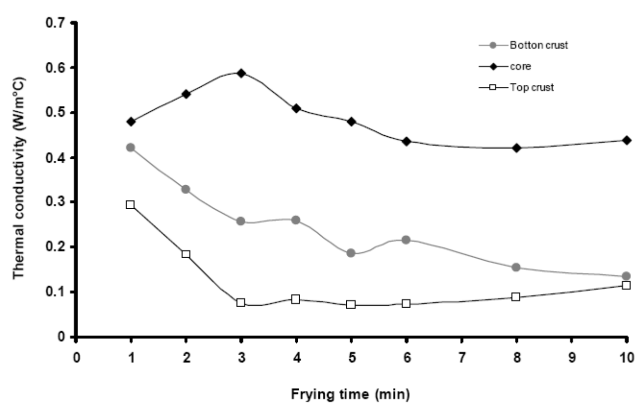


Figure 2. Thermal conductivity variation at different zones of French fries (Ziaiifar *et al.*, 2009)

### B. 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:

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

*where, $h_c$ convective heat transfer coefficient ($Wm^{-2}K^{-1}$), A surface area ($m^2$), q heat flow ($js^{-1}$), $T\infty$ 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 ($Jkg^{-1}C^{-1}$), $\rho_w$ water density ($kgm^{-3}$), ε water volume fraction and (L −δ) is crust thickness.*

## IV. 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 modeling of frying process there is still work needed to improve this process and quality of product. 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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