EXPERIMENTAL VERIFICATION OF TRANSPORT PHENOMENA DURING FRYING OF FOODS

BY

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DISSERTATION

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Abstract

Experiments were performed to measure moisture loss, fat uptake, heat transfer coefficient and mechanical properties of fried foods. The measured properties and variables were used in a Hybrid Mixture Theory based model solved using the finite element method to elucidate the phenomena affecting fat uptake. This provided further clarity on mechanisms involving fat uptake and helped develop avenues to reduce fat content of fried foods.

Frying experiments were performed at two temperatures of 175°C and 190°C for 200 s and 240 s for potato discs and chicken nuggets, respectively. The gage pressure increased rapidly above the atmospheric pressure immediately after the samples were introduced into the hot oil. The rise in pressure was greater in potato discs with greater initial moisture content. This was expected due to rapid moisture flash-off. As frying progressed, the temperature inside the samples increased whereas the gage pressure started decreasing and became negative. The onset of suction or negative pressure was observed during initial stages of frying for chicken nuggets, but in the middle of frying for potato discs. The negative pressure values before the product was taken outside the fryer may cause increased oil uptake during frying itself. During the post frying cooling, the pressure further decreased and reached negative values. The negative pressure was expected to have caused rapid absorption of surface oil during both frying and cooling stages.

The effect of frying parameters (temperature and time) on the properties of potato slices (surface pore characteristics, oil content, moisture loss and mechanical properties) was investigated. Scanning electron microscopy (SEM) was employed to develop surface topographic images and image pro plus software was used to determine the pore area of
potato slices. The rheological behavior of potato slices was investigated using dynamic mechanical analyzer (DMA). Both frying temperature and frying time had a significant impact on the pore area, creep behavior, moisture loss and fat uptake of potato slices. The changes in surface porous structure (pore area) and creep compliance were dynamic and in turn affected the oil uptake and moisture loss rates. Average open pore area and percent open pore area increased to $1.15 \, \mu \text{m}^2$ and 14.04%, respectively, during middle frying stages. Higher frying temperature resulted in faster structural degradation, moisture loss and oil uptake during initial frying stages. Higher frying times tended to increase the percentage open pore area.

The convective heat transfer coefficient was also measured experimentally using a controlled one-dimensional frying methodology. Hollow Teflon disc was used as a sample holder. Thermostable silicon glue was used to seal the sample in the Teflon disc. This insulated the edges of the potato disc from the frying oil thus restricting oil penetration from only the exposed top and bottom surfaces. This also rendered this set of frying experiments a one-dimensional frying process. The peak heat transfer coefficient values were determined to be 3617, 4517 and 7307 W/m$^2$°C at frying temperatures of 150, 170 and 190 °C, respectively. The heat transfer coefficient reached its peak value towards the end of frying at all temperatures.

Involvement of unsaturated transport and high temperatures during frying of foods makes it a challenging process to study via experiments and computer simulations. The hybrid mixture based unsaturated transport theory of Takhar (2014) was validated via controlled frying experiments. A hollow Teflon disc was used to insulate the edges of potato disc to ensure that frying was controlled, one-dimensional, and oil uptake and moisture loss happened only through top and bottom surfaces. The model was used to predict moisture and oil content, evaporation rates, temperature distribution, and pore and gas pressure profiles as a function of
frying time and temperature. Percentage average absolute difference (AAD) between predicted and experimental values for moisture content was 3.89%, 5.7% and 5.5% and oil content was 14%, 31% and 20% at 150, 170 and 190 °C respectively. Simulations showed that oil penetrated to only 0.25mm into the potato disc. Removal of surface oil improved the prediction of experimental oil content. Maximum evaporation rate of 0.32 kg/m$^3$s was observed near the surface of potato slice at 60 s frying time resulting in rapid moisture loss. Pore pressure remained negative beyond 60s frying time, which may act as a driving force for oil uptake.
Acknowledgement

Completing the PhD degree is probably my greatest achievement so far in the first 30 years of my life. I have shared the highs and the lows of this upward journey with many people. It has been my greatest privilege to earn my doctorate in the Department of Food Science and Human Nutrition at University of Illinois Urbana-Champaign. The people I met, and the friends I made here, will always remain close to my heart.

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Introduction

Fried foods in their raw form are moist and generally high in moisture content. What makes frying a very popular cooking process is the faster cooking achieved by high rates of heat transfer, which other cooking processes fail to achieve. The high rates of heat transfer are achieved due to the rapid heat transfer through convection and conduction from the oil to the food. This rapid heat transfer results in extremely fast moisture loss resulting in development of a crisp and crunchy exterior and a soft interior. High frying temperature also causes flavor and taste development preferred by the consumers.

Along with the enjoyable texture and flavors developed during frying, there is a big concern regarding the fat content of fried foods. As fried foods are very popular with the consumers, the over consumption of fried foods has been related to obesity. Thus, there is an increased focus by the fried foods industry to reduce the fat content of fried foods. Although, there has been a significant amount of research on exploring the mechanisms of oil uptake and reducing the fat content in fried foods, there is still not enough clarity on the mechanisms. Therefore, the main objectives of the current study are to explore the mechanisms involved during frying that affect fat uptake, texture development, and heat and mass transfer.

The present study focused on experimental verification of the transport mechanisms during frying of foods. The purpose of the frying experiments was to obtain the diffusive and mechanical properties of fried foods and to obtain better understanding of the transport mechanisms. Frying is a complex process in which
simultaneous transfer of heat and mass occurs between the frying medium (hot oil) and the food material. In order to improve the frying process it is vital to understand the transport mechanisms and the driving forces behind those transport mechanisms.

Two important factors affecting the oil uptake in foods during deep fat frying are water content and pressure development. In the past frying studies, the physical pressure was not measured experimentally but was calculated using computer models, which has resulted in disagreements about its magnitude. The first part of the study tries to explain the complex mass transfer mechanisms taking place during deep fat frying with respect to real time pressure variations inside potato discs and chicken nuggets.

In the second part of the study, the effect of frying parameters i.e. frying temperature and frying time on the properties of potato slices (surface porous characteristics, oil content, moisture loss and mechanical properties) was studied. Scanning electron microscopy (SEM) was used to study the surface porous characteristics and rheological behavior was investigated using dynamic mechanical analyzer (DMA). The pore area of the potato slices was determined by analyzing the SEM images while the rheological behavior was studied by measuring the creep compliance function using a four element Burger’s model.

The transport processes during frying depend largely on the heat transfer and mass transfer coefficients. Thus, in the third part of the study the convective heat transfer coefficient was measured using controlled frying experiments. The convective heat transfer coefficient was measured experimentally using a controlled one-
dimensional frying methodology. Hollow Teflon disc was used as a sample holder. Thermostable silicon glue was used to seal the sample in the Teflon disc. This insulated the edges of the potato disc from the frying oil thus restricting oil penetration from only the exposed top and bottom surfaces and rendered this set of frying experiments a one-dimensional frying process.

In the final part of the study, the properties and variables measured during the frying experiments were used to validate the Hybrid Mixture Theory (HMT) based unsaturated transport theory of Takhar (2014). The convective heat transfer coefficient measured during controlled frying experiments was used as a boundary condition in the heat transfer portion of the frying model. Model validation was performed by comparing predicted and experimental oil content values, after removing the surface oil, which was expected to have penetrated during post-process cooling. Thus, testing HMT based equations in a controlled one-dimensional flow provided a better estimate of oil, moisture and temperature profiles than three-dimensional flow. The temperature data was also obtained at different locations to facilitate model validation. HMT based equations were solved using finite element method to obtain profiles for moisture, temperature and oil content.

**Objectives:**

Main objectives of the research are to:

a) Determine pressure changes inside the foods during frying as a function of frying time, temperature and location.
b) Investigate texture development by measuring creep compliance and studying the surface porous characteristics of potato slices as a function of frying time and temperature.

c) Measure the convective heat transfer coefficient using controlled frying experiments.

d) Validate the HMT based model by conducting controlled frying experiments.
Chapter-1

Experimental Measurement of Physical Pressure in Foods During Frying

1.1 Introduction

During frying, heat is transferred from the heated oil to the food product (Erdogdu & Dejmek, 2010). Simultaneous heat and mass transfer occurs in which water evaporates from the food and oil migrates into the product (Krokida, Oreopoulou, & Maroulis, 2000). The absorbed fat is the most important quality attribute of fried products and has become a public health concern. Although the consumer trend is toward healthier fried products, they are not willing to sacrifice the taste and flavor (Bouchon, 2009). Therefore, to obtain fried products with lesser fat content, it is vital to understand the mechanism of frying processes, i.e., driving forces for oil uptake and moisture loss (Bouchon & Pyle, 2005).

Pravisani & Calvelo (1986) suggested frying to be a moving boundary layer process, in which the boundary layer separates the crust and the core. Moisture loss from the product has been described as a diffusion mechanism (Krokida et al., 2000), in which water migrates from inside the core to the boundary layer before leaving the product through the surface as vapor (Ziaiifar, Courtois, & Trystram, 2010). Kassama & Ngadi (2004) stated that the evacuation of moisture creates pores in the product, which provides a path for the entry of oil in the product. Although the counter flows of
moisture and oil are related, they do not take place at the same time, but occur sequentially (Bouchon & Pyle, 2005).

Oil uptake is a complex phenomenon, which is not clearly understood. Several factors such as product structure, interactions between product and heating medium, variation in product and oil properties make the frying process complicated (Mir-Bel, Oria, & Salvador, 2009). Oil uptake has been defined as a surface phenomenon and it has been stated that oil does not enter the product to great extent during frying but is drawn inside from the surface film after the product is taken out of the fryer (Moreira, Sun, & Chen, 1997; Ziaiiifar et al., 2010). Saguy & Dana (2003) described that the oil uptake occurs by two mechanisms - continuous replacement of moisture by fat, and fat absorption after frying.

During frying, the moisture in the product is converted to vapor and a vapor gradient is created in the product (Krokida et al., 2000). This vapor gradient prevents the oil uptake into the product (Bouchon & Pyle, 2005). During post frying cooling, the vapors collapse due to cooling and subsequent condensation leading to negative pressure gradients and forcing the oil from outside to inside the product (Saguy & Dana, 2003).

Most research agrees that oil uptake is a pressure driven phenomena mediated by capillary forces (Bouchon & Pyle, 2005). The pressure gradient inside the product undergoing frying is of great importance in further understanding the mechanisms of oil uptake and moisture loss. Moreira et al. (1997) and (Ni & Datta, 1999) calculated the pressure gradient inside the fried product but no data is available on measured pressure
changes inside the product undergoing frying. Vitrac, Trystram & Raoult-Vac (2000) experimentally measured the pressure changes during frying and cooling of an alginate gel formulated with starch. They concluded that most of the oil penetrated the gel during cooling stage due to low-pressure. The fact that the oil uptake depends on the low-pressure values, stresses the need to measure pressure inside the actual product during frying and cooling.

Several authors have described the mechanism and kinetics of oil uptake during frying and most agree that in order for the oil to penetrate the food there needs to be a driving force that forces the oil into the food (Durán, Pedreschi, Moyano, & Troncoso, 2007). Bouchon & Pyle, (2005), Moreira, et al., (1997) and Pinthus, Weinberg & Saguy (1995) agree that the low pressure values or the vacuum effect is the main driving force behind the oil uptake. They further state that oil uptake starts once the vacuum effect takes place. Pressure measurement inside the food during frying will measure the amount of driving force, i.e., pressure, and will indicate the time at which vacuum effect starts during frying. This will give an idea about the point at which the oil uptake begins during frying. This could happen during frying as well as during the cooling stage.

The main objective of this study is to measure experimentally the pressure changes occurring inside the product during frying and cooling stages, and relate them to oil uptake. This study will supplement earlier findings to better understand the mechanisms of oil uptake and moisture loss as a function of pressure gradient inside the food during frying and cooling.
1.2 Materials and Methods

The frying experiments were conducted with two food products, potatoes and chicken nuggets. Potatoes of Russet variety were obtained from a local grocery store. This variety is commonly used for making French fries. Chicken nuggets were made from full breast meat in a food company. The nuggets were breaded with methylcellulose coating. Crisco brand vegetable shortening was used as the frying medium.

The potatoes were peeled using a ceramic peeler. The peeling was done very softly to minimize damage to the potato surface. Potatoes were then sliced into 8 mm discs using a stainless steel knife. The thickness was measured using a Vernier caliper. The discs were then cut into circular discs of 46 mm diameter using a cookie cutter. This was done to ensure all the discs were of uniform shape and size. The discs were dipped into water bath for 3-5 minutes, so that the starch on the surface was washed away. The discs were dried manually by patting them gently using paper towel. Chicken nuggets were par-fried at 176 and 190°C and were kept frozen at -12°C prior to the full frying experiments. Chicken nuggets were thawed at room temperature for 1 hour before full frying experiments. The initial temperature of the product was maintained at 25 °C to ensure similar initial conditions for all iterations.

The samples were fried in a table-top fryer (GE, Model No. 169219 electric fryer) with an oil capacity of about 3 liters. The oil was preheated at the set temperature for 1 hour before each frying trial. This ensured homogeneous temperature throughout the oil. Frying was performed at two temperatures of 176 and 190°C for 200 s and 240 s for potato discs and chicken nuggets, respectively. Two frying temperatures were selected...
to study the temperature effect on pressure changes inside the samples. Samples were fried individually on a perforated stainless steel frying basket.

After completion of frying, the samples were shaken lightly 5 times to remove surface oil from them. They were left in the frying basket for cooling time equivalent to frying time at room temperature conditions. Thus, the total experiment time was 6 minutes and 40s, with frying time of 3 minutes and 20 s followed by an equivalent cooling period.

1.2.1 Pressure Measurement

The pressure was measured using a fiber optic pressure sensor connected to a FTI fiber optic conditioner (FOP-MH-NS-556, FISO Technologies Inc., Quebec, Canada). The conditioner was connected to computer and the data was recorded using FISO commander software (FISO Technologies Inc., Quebec, Canada), which was further analyzed in Microsoft Excel.

The pressure was measured at the center of the sample as well as near the surface. Measuring pressure near the surface and at the center provided information about the movement of the pressure front into the sample during the frying and cooling stages. For the measurement of pressure, a 22 mm long cavity was made in the sample using a 2.2 mm diameter stainless steel needle. The pressure sensor was then inserted into the cavity. The sensor was 2.8 mm in diameter and fitted firmly into the cavity. After inserting the sensor in the cavity, the sample material was gently compacted around the sensor and the wire. This procedure ensured that there was no gap between the wire and the wall of the cavity. It also prevented any direct contact between the
sensor tip and frying oil. At the end of each frying experiment, the sample was examined to ensure no gap was formed around the sensor during frying. At the end of frying, the food material was observed to be sticking around the sensor wire. This indicated that the food had sealed the sensor due to which, the measured pressure changes were expected to be realistic.

The temperature inside the samples was measured using a thermocouple connected to a data logger (NI9600, National Instruments, Austin, U.S.A). The temperature was recorded in a computer using Labview software (National Instruments, Austin, Texas, U.S.A). The data was further analyzed using Microsoft Excel. The temperature inside the samples was also measured near the center and surface. For measurement of temperature the thermocouple was inserted in the sample to about 22 mm inside along the radius. Measuring temperature inside the samples helped to relate the temperature changes occurring during frying and cooling stages to the pressure changes. A 3x2x2 factorial design, with 3 replications each at surface and center of the sample, was used.

Three samples of potato discs and chicken nuggets were fried at two frying oil temperatures. The pressure and temperature were measured at two points (surface and center) in the samples in two trials. Each treatment was replicated three times.

1.3 Results and Discussion

1.3.1 Potato Discs

Potato discs were fried in oil from initial moisture content of 326% dry basis (d.b) to 202% d.b at 176°C and 177% d.b at 190°C. Higher temperatures of frying oil caused
greater moisture loss. The final fat content of the fried potatoes was also higher at higher frying temperature. The fat content of the products fried at 176°C and 190°C were 66.2% d.b and 78.9% d.b, respectively.

1.3.1.1 Temperature and Pressure Profiles Inside Potato Discs

The temperature inside the product increased rapidly for the initial period of frying and later reaches a plateau during the final stages of frying time. Figs. 1.1-1.2 and Table 1.1 show the temperature and pressure profiles at the center and near the surface of potato discs fried at two different temperatures of 176 and 190°C. However, the temperature does not drop rapidly during the cooling period but instead drops slowly by about 10°C in magnitude. Ni & Datta, (1999) observed the evaporation temperature to be 90 °C. However, the maximum temperature during the experiments conducted in this study reached above 100 °C. When the moisture content becomes low at a point inside the potato disc, the effect of evaporative cooling is mitigated, and the temperature may become more than the boiling temperature due to penetration of high temperature oil.

The pressure inside the product rises rapidly along with the rise in temperature during initial frying stages (Figs. 1.1-1.2). This can be attributed to the build up of vapor pressure inside the cellular structure of potato tissue, which increased the pressure on the sensor tip. The build up of pressure continues till a maximum value of temperature is attained inside the product beyond which it reaches a plateau. Ni & Datta, (1999) also reported the pressure to rise with evaporation and attaining a maximum value at the evaporation front. During the latter stages of frying, the pressure drops rapidly and
attains a negative value at the end of frying. The pressure stays negative throughout the cooling period, but the drop was not as steep as it was during the frying period.

The pressure drop inside the product could be due to the collapse of the cellular structure, escape of vapors from the cellular cavities, capillary forces or a combination of these factors. The negative pressure inside the product is expected to enhance the oil uptake. This negative pressure can act as a driving force for oil uptake inside the product. The pressure drop begins during middle of frying period, which may result in the oil uptake and absorption during frying. Moreira, et al., (1997) reported that for tortilla chips only 20% of the oil uptake happens during frying while 64% of final oil content is absorbed during cooling period. The pressure drop during the frying period may initiate the movement of oil into the product during the frying stage itself, which continues till the end of frying. When the product is taken out of the oil for cooling, the oil is expected to be distributed non-uniformly between the surface and interior of the product as shown during numerical simulations by (A. Halder, A. Dhall, & A. K. Datta, 2007b). The continuous pressure drop and negative pressure during cooling can act as a mechanism, which further forces the oil from the surface to move into the core of the product.

1.3.1.2 Effect of Temperature and Position

Potato discs fried at 190°C show a higher buildup of pressure at the center than the samples fried at 176°C. This can be due to the higher core temperatures attained at high frying oil temperature. The greater pressure build up at the higher frying oil temperature is accompanied by subsequently low values of pressure. This high pressure
followed by higher magnitude of negative pressure can be the reason for greater oil uptake in case of samples fried at 190°C (66.2% at 176°C and 78.9% at 190°C).

At the surface of the samples, higher temperature is attained for lower frying oil temperature, which can be the reason for higher-pressure buildup (Fig. 1.2). However, higher magnitudes of negative pressure are attained for higher frying oil temperature. The negative pressure inside the sample is important as it is directly correlated to the final oil content of the product.

1.3.2 Chicken Nuggets

Chicken Nuggets were fried in oil from initial moisture content of 100% to final moisture content of 72% at 175°C and from 111% to 78% at 190°C. Greater amount of percentage moisture loss was observed at higher frying oil temperature. The final oil content of the chicken nuggets was 40.4% and 44.4% at 175°C and 190°C respectively. This indicates a greater amount of oil uptake at higher frying temperature.

1.3.2.1 Temperature and Pressure Profiles Inside the Chicken Nuggets

Figs. 1.3 and 1.4 and Table 1.2 show the pressure and temperature profiles near the surface and at the center of chicken nuggets for frying and cooling period. Chicken nuggets were fried for a period of 4 min and later cooled at room temperature for an equivalent time period. As in case of potato discs, chicken nuggets were also thawed to room temperature to ensure similar starting points for all samples. The temperature inside the chicken nuggets rises at a constant rate during the frying period and remains almost constant during the cooling period. The drop in temperature inside the nuggets
is insignificant at the center while it drops by about $8^\circ$C during the cooling period at the surface.

As the temperature in the chicken nuggets rises at a slower rate it delays the buildup of pressure. When the temperature reaches the evaporation point, the pressure starts to rise in the nuggets. This can be attributed to the vapor pressure exerted by the water vapors on the cellular structure of the chicken nuggets. As soon as the temperature inside the chicken nuggets reaches the maximum value the pressure suddenly drops and stays negative throughout the cooling period. The pressure values for chicken nuggets are not of the same order as for potato discs. This could be due to the lesser moisture content in nuggets or the tender structure of chicken nuggets, which exerts lesser force on the tip of the sensor. The pressure inside the chicken nuggets remains negative throughout the frying and cooling periods for all samples. This negative pressure inside may result in the oil uptake throughout the frying period. The sudden drop in the pressure inside the nuggets during the cooling period may result in the absorption of surface oil into the interior of the nuggets.

The pressure profile and the absolute pressure values are similar for all the samples. The buildup of pressure inside the nuggets is greater at higher frying oil temperature at both surface and center of the nuggets.

### 1.4 Conclusions

There is a buildup of pressure inside the product due to the increasing product temperature. The pressure increase was greater for samples with higher moisture content. During the frying stage itself, the gage pressure attained negative magnitudes.
The drop in pressure to the negative values may act as a driving mechanism for the uptake of oil before the product is taken out of the fryer. The constant negative values of pressure during the cooling period are expected to result in the further absorption of oil from the surface to the core.
Fig 1.1 Temperature and pressure profiles at 175 and 190°C at the centre of a potato disc
Fig 1.2 Temperature and pressure profiles at 175 and 190 °C near the surface of a Potato Discs
Fig 1.3 Temperature and pressure profiles at 175 and 190°C at the center of chicken nuggets
Fig 1.4 Temperature and pressure profiles at 175 and 190°C near the surface of chicken nuggets.
### Table 1.1. Temperature and pressure values at surface and centre for potato disc

<table>
<thead>
<tr>
<th>Exp Type</th>
<th>175°C, center</th>
<th>190°C, center</th>
<th>175°C, surface</th>
<th>190°C, surface</th>
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</thead>
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<tr>
<td>Value</td>
<td>Temperature(°C) Pressure(Pa)</td>
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<td>Avg. Std Error</td>
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### Table 1.2. Temperature and pressure values at surface and centre for chicken nuggets

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<th>Exp Type</th>
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<th>190°C, center</th>
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<tbody>
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<td>Value</td>
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<td>Temperature(°C) Pressure(Pa)</td>
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Chapter 2

Effect of Frying Parameters on Mechanical Properties and Microstructure of Potato Discs

2.1 Introduction

Frying is an important industrial process during which the food is immersed in hot oil. During frying, heat is transferred from the hot oil to the product. The heat transfer results in moisture loss and thermal degradation. The food material softens due to thermal degradation, and as the frying progresses, the product looses its moisture. The loss in moisture depends on frying time and results in the hardening of the product structure. Therefore, both thermal degradation and structural hardening are functions of temperature and moisture content (Thussu & Datta, 2012).

The textural attributes of fried potato product are one of its most important qualities. These include thin crispy exterior (crust) and soft interior. Frying results in formation of a thin crust due to advancement of dehydration front towards the center of the product. This is accompanied by tissue disruption, starch gelatinization, pore formation and change in shape and size of the cells (Kalogianni & Papastergiadis, 2014). These changes also result in mass transfer in the form of moisture loss and fat uptake during the frying process. In order to obtain a clear understanding of the complex mass transfer processes, it is vital to characterize the surface porous structure of the fried products (Dueik, Moreno, & Bouchon, 2012).
Moreno, Brown, and Bouchon (2010) suggested that the surface properties of the fried products are very important in understanding oil absorption during frying. They further stated that the surface topography of the fried product should be accurately measured and employed scanning laser microscopy (SLM) to study the surface characteristics of fried foods. Llorca, Hernandez, Perez-Munuera, Fiszman, and Lluch (2001) also employed the scanning electron microscopy technique to study the surface properties like pore size to understand oil absorption during frying of battered frozen squid rings. However, there are very limited studies on product microstructure as a function of frying time. Therefore, it is important to characterize the changes in surface porous structure as a function of frying time to further elucidate the mechanisms involved in oil uptake during the frying process.

Along with product microstructure, it is also important to study the mechanical properties of the food in order to understand their texture and rheological behavior. Texture development during frying can be characterized by measuring the mechanical properties of potato discs as a function of frying temperature and time. Kita, Lisinska, and Golubowska (2007) and Krokida, Oreopoulou, Maroulis, and Marinos-Kouris (2001) characterized the textural changes during frying by measuring the mechanical properties of the potato products.

Several researchers have shown that most fruits and vegetables, including potatoes, exhibit viscoelastic behavior (Alvarez, Canet, Cuesta, & Lamua, 1998). The viscoelastic properties are a function of the viscous and solid components of food. During frying, both the viscous and solid components are affected by moisture loss, oil
uptake, starch gelatinization and crust formation (Lima & Singh, 2001). In order to
determine the viscoelastic properties of a food matrix, transient and dynamic tests can
be performed (Li, Li, Wang, Özkan, & Mao, 2010). Most common of these tests are creep
compliance, stress relaxation and dynamic oscillatory test (Halim & Shoemaker, 1990).

One of the important properties of a viscoelastic material is that they undergo
creep i.e. continue to deform under constant stress. Alvarez et al. (1998) stated that
creep compliance tests can better characterize food texture than other tests involving
stress relaxation. Several researchers have used the creep compliance tests to
investigate the viscoelastic behavior of different foods (Halim and Shoemaker (1990);
Ditudompo, Takhar, Ganjyal, and Hanna (2013); Jackman and Stanley (1995). The main
advantage of creep compliance tests is that larger number of rheological parameters
can be estimated. These rheological parameters include elastic, viscoelastic and viscous
flow characteristics of a food (Alvarez & Canet, 1998).

In creep compliance testing, the food material is subjected to a constant stress.
When the load is applied normal to the surface (tension or compression), the creep is
caused by the change in thickness of the material. The food material thus undergoes
compression and deforms. The deformation is measured as a function of time. The
deformation data is fitted nonlinearly to a Burgers model to estimate the rheological
parameters. In this study, creep compliance testing was carried out using the dynamic
mechanical analyzer (DMA). The creep compliance data was further fitted to a four-
element Burgers model using non-linear fitting.
The four-element Burgers model can be described by the following equation:

\[ J(t) = J_0 + J_1 \left( 1 - \exp\left( -\frac{t}{\lambda_{ret}} \right) \right) + \frac{t}{\mu_0} \quad \text{(Equation 1)} \]

\( J(t) \): compliance at time \( t \)

\( J_0 \): instantaneous compliance at time \( t = 0 \)

\( J_1 \): compliance of Voigt unit

\( \lambda_{ret} \): retardation time

\( \mu_0 \): viscosity

Potato is the world’s largest tuber crop and the fried potato products (French fries and potato chips) are its largest commercial end product (Pedreschi & Moyano, 2005). Potatoes are high in starch content, which makes them ideal to be used as a raw material for frying. High rates of heat transfer and rapid loss in moisture during frying results in development of crunchy exterior and soft, moist interior in case of French fries and crisp texture in potato chips. Therefore, the objectives of this study are to study the textural changes occurring in potato discs as a function of frying time and temperature and to elucidate the changes in surface porous structure of fried foods as a function of frying time. Frying time and temperature both have an effect on moisture loss and oil uptake, which affect the texture and product microstructure. These changes are characterized by measuring the creep compliance function using the dynamic mechanical analyzer (DMA) and surface porous structure through analysis of the images obtained by scanning electron microscopy (SEM). The viscoelastic properties measured by fitting the data to Burgers model and surface pore properties (pore area) measured
using Image Pro Plus software will be useful for modeling studies and to further understand the transport mechanisms during frying of foods.

2.2 Materials and Methods

2.2.1 Sample Preparation

Potatoes of Russet variety obtained from a local grocery store were used in the frying experiments. This a common variety used to produce French fries and potato chips. Potatoes were peeled using ceramic peeler and sliced to an average thickness of 1.5±0.1 mm (required as per industry specifications). The potato discs were washed in cold water for 30 s to remove surface starch. The excess moisture on the discs was removed using absorbent paper towels. Any discs smaller than 40 mm diameter were discarded to ensure size uniformity.

Frying was carried out on tabletop gas fryer with an oil capacity of 3 liters (GE, Model No. 169219 electric fryer). 138 grams of potato discs were fried in a single batch. Sunflower oil was used as the frying medium. A constant product to oil ratio of 0.046 (as per industry specifications) was maintained to ensure uniform frying conditions for all replications. Constant product to oil ratio ensured uniform heat load and frying temperature profiles during frying experiments. Frying was carried out at 165, 182 and 199 °C. As the product to oil ratio was low (0.046) during each frying experiment, the set oil temperature did not vary beyond 5°C (± 2.5 °C) during each experimental run. The samples were fried for 20, 40, 60, 80, 100, 120, 140, 160, 180, 190, 200 and 220 s. Samples were constantly stirred till 120 s frying time. Beyond 120 s the samples were
completely submerged until frying ended. 12 frying batches were fried at each


temperature. The oil was changed after all batches at one set temperature were fried.


Post-frying samples were allowed to cool for a few s on the frying basket and

were shaken 5 times to remove the excess oil. Samples were then immediately dipped

in liquid N$_2$ and hermetically sealed in metallized bags. The sealed bags were then

stored at -80 °C until further analysis.


2.2.2 Moisture and Fat analysis

The frozen fried samples were ground into powder using a coffee grinder, which

was precooled using liquid Nitrogen. Precooling the grinder ensured that the ground

powder didn’t stick to the grinder walls. The grinding resulted in a homogeneous sample

and allowed for effective moisture and oil extraction. The powdered samples were

analyzed for moisture content in an automatic moisture analyzer (Model: OHAUS MB35,

OHAUS Corp). Moisture meter was calibrated against AOAC method no. 934.01

(International, 1995). Frozen ground samples were prepared using grinder with each

sample weighing about 0.5 grams. Powdered sample was spread thoroughly over the

aluminum pans and placed over the pan support of moisture meter. Halogen element

inside the moisture meter provides uniform infrared heating up to 160°C in less than a

minute. It heats the sample at a set temperature of 105°C until the sample weight

becomes constant. Moisture percentage as a function of weight change was recorded

and displayed. The moisture content values measured by the moisture meter were

converted to the AOAC method no. 934.01 (International, 1995) values using the

calibration curve.
Fat analysis was carried out using the Soxhlet method based on modified AOAC official method 991.36 (International, 1995). All fat and moisture analysis was carried out in triplicates.

2.2.3 Creep Compliance Tests

Dynamic mechanical analyzer (DMA) was used to study the creep behavior using the compression clamp. The fried potato samples were cut to a small disc of average diameter of 18±0.5 mm and 4 such discs were stacked on top of each other to form one single sample of thickness 6±0.5 mm. The four discs were then sealed using a polyethylene wrap. The sealing of samples ensured minimal moisture removal during DMA analysis. Each experiment was carried out in triplicates and average values were used in analysis.

Creep tests were performed at 37, 80 and 120 °C. However, only 37°C values were used in the data analysis as at 80 and 120 °C there was significant moisture loss during creep analysis. Temperature, preload force, constant load, soak time, creep time, recovery time and dimensions were the variable parameters, which were set before running the creep test. A preload force of 0.0001 N was applied to make the sample flat and have good contact with the DMA attachment. The constant load of 0.0030 MPa was applied to the samples to study their creep behavior. This was selected as it was just below the peak load that the samples could bear without breaking. Soak time (time required for the sample to reach testing temperature), creep time (time duration for creep testing) and recovery time were kept as 0.5, 1.5 and 1.5 minutes respectively. Five trials were performed for each temperature. Creep Compliance values measured by
DMA was obtained as a function of frying time and temperature. Maximum creep compliance was selected to study the effect of frying time and temperature on creep behavior of potato discs.

2.2.4 Scanning Electron Microscopy Tests

Two discs per frying time point were extracted out of the liquid nitrogen cooled samples. Potato discs fried at 182 °C were used in SEM tests. They were freeze-dried using freeze sublimation equipment (Kinney Vacuum, KSE-2A-M evaporator) to preserve the microstructure. Freeze-dried samples were deoiled using hexane to completely remove absorbed oil. For de-oiling, samples were dipped in hexane for 30 minutes and then kept under the exhaust hood for 5 minutes. The samples were then shifted to hot air oven for 10 minutes, so that hexane vaporizes completely without affecting the microstructure of the discs. Freeze dried and deoiled samples were then analyzed under the scanning electron microscope (Hitachi TM1000 table top microscope). Images were captured of the top surfaces at the middle and at the edge and at the vertical cross-section of the chip using graphical user interface software. Resolution employed during scanning electron microscopy was 80x.

2.2.5 Image Analysis

Greyscale SEM images obtained were analyzed using Image Pro Plus Software version 7 (Media Cybernetics). All the greyscale images were 8 bit. Therefore, the pixel intensity range is from 0 (black) to 255 (white). As SEM imaging is a surface imaging technique thus, the cracks and crevices appear darker than other surfaces. Therefore, the open pores appeared as darker areas on the image. The intensity threshold of open
pores was from 0-64. Open pores were separated from the rest of topographic features using the intensity filtering technique in the software. The free hand polygonal tool in the software was used to map the perimeter of the open pore to form an ellipse of an equivalent area. The area of the resultant ellipse was measured using the software to determine the pore area as a function of frying time. Pore size distribution was also similarly measured.

2.2.6 Data Analysis

The moisture and fat values obtained were analyzed using Microsoft Excel and SAS (Version 9.3, SAS Institute Inc., Cary, N.C). The creep compliance were used and fitted in Burgers model by non-linear fitting in Matlab (Version R2013a, Mathworks, Natick, MA). The rheological data obtained during nonlinear fitting was plotted as a function of frying temperature and time using Microsoft Excel.

2.3 Results and Discussion

2.3.1 Moisture and Fat Profiles during Frying

Most of the moisture loss and fat uptake happened in the initial stages of frying, i.e., till 100 s (Fig 2.1 and Fig 2.2). Beyond 100 s frying time the rates of moisture loss and fat uptake dropped considerably (near constant moisture content). Several researchers have reported similar results (Krokida et al., 2000; Pedreschi & Moyano, 2005; Yagua & Moreira, 2011). During initial stages of frying, faster rates of moisture removal (>90%) and oil uptake (>95%) were achieved at higher frying temperatures. This is consistent with the findings of Pedreschi and Moyano (2005) and (Vitrac et al., 2000)
who stated that higher rates of heat transfer are achieved at greater frying temperatures. The faster heat transfer results in faster initial heating and quick removal of free water in the foods. This results in faster moisture removal and oil uptake.

Higher frying temperatures resulted in a finished product with lesser moisture level and higher fat content similar to results obtained by Krokida et al. (2000) (Fig 2.3). Furthermore, Sandhu, Bansal, and Takhar (2013) reported that a higher frying temperature resulted in greater initial pore pressure buildup. The greater initial pore pressure resulted in faster pressure drop during frying, which increased the pressure gradient inside the product. This increased pressure gradient at higher frying temperature resulted in negative gage pore pressures during the post frying stage. This may provide greater driving force for moisture loss and fat uptake.

2.3.2 Creep Compliance Tests

The creep curve can be subdivided into four main regions (Fig. 2.4). O-A, A-B and C-D are straight lines while B-C is the curved portion of the curve. O-A is the region of instantaneous deformation and occurs instantaneously as soon as the load is applied on the sample under test. This is the region where the structural elements are compressed elastically. If the load is removed during this period of compression, the material will return to its original structure due to the potential energy stored in the test sample (Xu, Xiong, Li, & Zhao, 2008).

The region A-B is spread over initial period of compression (first few s) but is a part of the retarded elastic deformation, along with the B-C portion of the curve, which happens over longer periods of compression. This portion of the curve represents the
time dependent behavior of the sample and is responsible for the viscoelastic properties of the material (Alvarez et al., 1998). The region C-D is a straight line that represents the viscous deformation portion of the curve. During this period of compression the internal linkages in the sample tissues get permanently damaged. The removal of compressive load beyond this stage will result in only partial recovery to original structure (Xu et al., 2008). The extent of recovery under a constant load is determined by the textural properties of the sample.

The data from creep compliance curves was fitted into a 4-element Burgers model (equation 1) using non-linear fitting (Table 1). The data fitted well in the burger model equation. High correlation ($R^2$ between 0.98-0.99) was obtained between the predicted and experimental values. High $R^2$ values indicated the goodness of fit.

In general, when $J_0$ and $J_1$ are small, the heights of curve OA, AB and BC (Fig. 2.4) decreases, indicating lesser deformation and greater stiffness of the potato discs. Longer relaxation times ($\lambda_{ret}$) will result in decreasing slope of AB and BC portions of the curve. Decreasing slope indicates that the viscoelastic behavior is maintained for longer time periods. Lower $\mu_0$ values correspond to increased slope of C-D portion of the curve, showing decreasing viscosity of the potato discs (Xu et al., 2008).

The raw potato slice has low $J_0$ and $J_1$ values indicating that it is firm and deforms less under compressive force in comparison to the fried potato. Longer retardation time and low viscosity further indicates that, the firmness is maintained for long time during the creep test. However, as the discs are immersed in hot oil, for all frying temperatures, at 20 second frying time, $J_0$ and $J_1$ decrease and $\mu_0$ increases indicating
reduced stiffness due to softening of tissue structure. This trend continues as frying progresses to 60 s frying time. However at 199 °C frying temperature, $J_0$, $J_1$ and $\mu_0$ decrease indicating increased stiffness due to structural hardening. This further indicates faster rate of cooking at higher temperature. Also, due to faster moisture loss rates at 199 °C, the loss in moisture results in increased stiffness of potato discs.

As frying progresses to 100 and 120 s frying time, the effect of loss of moisture on the stiffness of the potato discs is substantial. $J_0$, $J_1$ and $\mu_0$ decrease further due to increasing stiffness behavior of potato discs. However, the increase in retardation time indicates that the behavior is more viscoelastic in nature. At 200 and 220 s frying time, the effect of oil uptake can be seen on the creep behavior of potato discs. The fat content increases as frying temperature increases. Thus potato discs fried at 165 °C exhibit maximum elastic behavior due to lowest $J_0$ and $J_1$ values.

### 2.3.3 Creep Compliance as a Function of Frying Temperature and Frying Time

Figures 2.5, 2.6 and 2.7 show the creep compliance $J(t)$ curves of the potato discs fried at 165, 182 and 199 °C for different frying times. The creep compliance curves in each figure are an average of 5 test samples. As creep compliance is a measure of deformation of a sample under constant isothermal stress, softer potato slice will creep (deform) more while a harder and crisp potato slice will creep (deform) less. When the sample is put under creep testing, the instantaneous creep compliance appears immediately due to instantaneous elastic deformation of the potato discs.
Subsequently, as the test progresses, the deformation occurs in a time-dependent manner due to the effect of retardation time.

Creep compliance depended strongly on both frying time as well as frying temperature (p<0.05), however the effect of frying time was more significant. This dependence is primarily due to varying degree of cooking exhibited at different frying temperatures and times. This variation in frying conditions resulted in different fat and moisture profiles at three frying temperatures. Thus the samples fried for different times and temperature behaved differently during creep testing. Potato discs fried at 165 and 182 °C showed maximum deformation at 80 s while for potato discs fried at 199 °C, maximum deformation was achieved at 40 s. This shows that starch gelatinization and rapid initial moisture removal is faster at 199 °C. Thus, higher frying temperature resulted in increased viscous behavior in lesser frying time. Similarly, potato discs fried at 165 °C showed minimum deformation at 220s, while for potato discs fried at 182 and 199 °C exhibited minimum deformation at 190s. This variation can be explained by looking at the creep behavior of potato discs as a function of frying time.

Fig. 2.8 shows the creep compliance function as a function of frying time. In the graph, creep compliance value at the end of creep test were selected and plotted as a function of frying time. In the beginning of frying the creep values increase as the frying progresses. This is because the potato discs are soft and flexible due to gelatinization of starch and have high moisture content and low fat content (surface fat). Pedreschi and Moyano (2005) stated that, for potatoes, which contain high amount of starch, major influence on texture is due to starch gelatinization. As the frying progresses, the fat
content of the discs increases and the moisture content reduces. However, fat uptake is less as compared to the moisture loss, with the latter due to higher rate of transport for the moisture. Thus, most of the fat uptake happens on the surface but the interior still remains uncooked. During this stage, creep values are dependent on starch gelatinization, and fat and moisture contents. Therefore, we observe increasing creep values from 20 to 80 s frying time for potato discs fried at 165 and 182 °C. Whereas at 199 °C the creep values increase only till 40 s of frying time indicating faster cooking, rapid moisture loss and increased fat uptake rates at higher frying temperature.

As the frying progresses beyond 40 s at 199 °C and 80 s at 165 and 182 °C, the creep compliance values start decreasing. This decrease is due to the onset of crust formation. However, the interior of the sample still remains soft, which results in high but decreasing values of creep compliance till 120 s. Beyond 120 s frying time the creep values become near constant due to structural hardening. During this stage, the cooking process is complete and frying takes place in purely hygroscopic range (Vitrac et al., 2000).

The creep compliance values are largely dependent upon the fat content of the sample. This is confirmed by the fact that higher frying temperatures result in greater fat content and greater creep compliance values at frying beyond 120 s. Similar results were also obtained by Krokida et al. (2001) who stated that as the oil content increases towards the end of frying, samples fried at lower frying temperatures exhibited greater stiffness or lower creep compliance values.
The creep compliance values as a function of frying time can thus be generalized in three different stages:

Stage 1 (0-80 s): Increasing creep compliance values due to starch gelatinization, moisture mobilization and surface fat uptake.

Stage 2 (100-160 s): Decreasing creep compliance values due to moisture loss and onset of crust formation.

Stage 3 (180-220s): Near constant creep compliance values due to structural hardening.

2.3.4 SEM Observations

Scanning Electron Microscopy (SEM) has been previously utilized by Llorca et al. (2001) and Aguilera, Cadoche, Lopez, and Gutierrez (2001) to study the surface porous characteristics of various foods. As described in the previous section the mechanical behavior of a food sample can be described using creep compliance analysis, but in order to visualize the textural changes it is vital to study the changes in cellular structure as a function of frying parameters (frying temperature and time). With SEM technique it is possible to visualize the cellular structure of a food sample, figures 2.9-2.12. The cells are polygonal in shape and enclose oval and spherical starch granules (Fig. 2.9). The surface is composed of large amount of open pores with an average pore area of 1.97 micron$^2$ and the open pores account for 30.67% (Fig. 2.13) of total surface area on one side of a potato disc. The open pores are a result of slicing action of potato slicer that cuts across cells resulting in open cells. This fact can be further explained by a closed
and compact structure in the crossection of the potato slice. At the crossection there are no open pores or capillaries in the raw potato slice.

However, as the frying began the starch granules dissolved and the cellular structure collapsed. This may be due to intense moisture removal, oil pressure, surface starch gelatinization and thermal degradation (Kalogianni & Papastergiadis, 2014; Llorca et al., 2001). This resulted in closing of most of the pores on the surface along with reduction in open pore area to 3.8% of the total area. The average pore area also reduced to 0.37 micron$^2$. The porous structure at the cross-section was still compact, closed and uniform with an average pore area of 0.72 micron$^2$ (Fig.2.14). This indicated that only surface of the potato slice is affected by the frying dynamics up to 20 s of frying. This justifies rapid surface moisture removal and comparatively low creep compliance values till 20 s of frying.

As the frying progressed both average pore area and percentage open pore area are affected. The average open pore area first increased at 40 s frying time to 0.72 micron$^2$ and later reduced till 80 s frying time to 0.37 micron$^2$. However, the average pore area at the crossection increased to 1.82 micron$^2$ indicating beginning of capillary formation. The capillary formation and an overall increase in average open pore area at the crossection also coincided with increase in creep compliance values. SEM images at 120 s frying time indicate a significant increase in number of open pores. This increase is quantified by an increase in both average open pore area to 0.85 micron$^2$ and percentage open pore area to 14.04% at 120 s frying time. Maximum percentage open pore area was also observed at 120 s frying time. The average pore size at the
crossection of the potato slice at 120 s frying time also increased indicating formation of large capillaries in the interior of slice. This may explain faster rate of fat uptake till 120 s of frying. However, there is a variation in average pore area showing presence of small and large capillaries.

Towards the end of frying till 190 s there was a marked reduction in both average pore area and percent open pore area along with reduction in creep compliance values indicating hardening of potato disc structure. The average pore area reduced to 0.4 micron$^2$ while the percentage of open pore area dropped down to 1.26% of total area. There was a great variation in average pore area at the crossection of potato slice in the latter stage of frying due to structural hardening. SEM images of fully fried (220 s) potato slice show that most of the surface pores have closed. However, there was an increase in average pore area and percentage open pore area. The average pore area increased to 0.94 micron$^2$ and the percentage open pore area also increased to 4.96%. This may explain a slight increase in final fat content of potato discs towards the end of frying.

2.4 Conclusions

Both frying temperature and frying time had impact on the creep behavior and microstructure of potato discs. Creep compliance values first increased during initial stages of frying. While average pore area and percentage open pore area decreased during initial frying stages due to rapid moisture loss and fat uptake. During middle frying stages (100-160 s) average pore area and percentage open pore area increased along with onset of capillary formation. As the frying progressed the creep compliance
values decreased and became near constant towards the end of frying. Whereas, the microstructure became closed and very few open pores could be observed. Higher frying temperature resulted in higher creep compliance values towards the end of frying. Higher frying temperature also resulted in shorter initial stage of frying resulting in faster cooking. Creep behavior of potato discs at all frying temperatures and times comprised mainly of instantaneous and retarded elastic deformation. Creep behavior also showed good correlation with the average moisture content during different frying stages. The average creep compliance values decreased with decreasing moisture content of potato discs.
Fig 2.1. Moisture profiles in potato discs as a function of frying time. Error bars indicate ± one standard error. Std. deviation range for the plot is: 0.13 to 22.06, number of replications per time point=3.
Fig 2.2. Oil uptake profiles in potato discs as a function of frying time. Error bars indicate ± one standard error. Std. deviation range for the plot is: 0.31 to 7, number of replications per time point=3.
Fig 2.3. Final Moisture and Fat Content as Function of Frying Temperature
Fig 2.4. General Creep Compliance Curve
Fig 2.5. Creep Compliance Curves at 165 °C Frying Temperature, dotted lines indicate burgers model fitted parameters.
Fig 2.6. Creep Compliance Curves at 182 °C Frying Temperature, dotted lines indicate burgers model fitted parameters.
Fig 2.7. Creep Compliance Curves at 199 °C Frying Temperature, dotted lines indicate burgers model fitted parameters.
Fig 2.8. Creep Compliance as a function of frying time and frying temperature. Error bars indicate ± one standard error. Std. deviation range for the plot is: $2.77 \times 10^7$ to $2.75 \times 10^8$, number of replications per time point=6.
Fig 2.9. SEM Images of raw potato disc depicting surface porous characteristics for center (a) and crossection (b) (magnification 80X).
Fig 2.10. SEM Images for potato disc fried for 20 s at 182 °C depicting surface porous characteristics for center (a), edge (b) and crossection (c) (magnification 80X).
Fig 2.11. SEM Images for potato disc fried for 120 s at 182 °C depicting surface porous characteristics for center (a), edge (b) and cross-section (c) (magnification 80X).
Fig 2.12. SEM Images for potato disc fried for 220 s at 182 °C depicting surface porous characteristics for center (a), edge (b) and crossection (c) (magnification 80X).
Fig. 2.13 Graph depicting average pore area and percent open pore area at the surface of potato disc as a function of frying time. Error bars indicate standard error to depict 95% confidence intervals for pore size distribution, range of pore area=0.3 – 2.3 μm², number of replications per time point = 3.
Fig. 2.14 Graph showing average open pore area at the crossection of potato disc. Error bars indicate standard error to depict 95% confidence intervals for pore size distribution, range of pore area = 0.56 – 5.6 μm², number of replications per time point = 3
Chapter-3

Experimental Determination of Convective Heat Transfer Coefficient during Controlled Frying of Potato Discs

3.1. Introduction

To model the frying process and the underlying transport mechanisms, it is vital to understand the convective boundary conditions for heat and mass transfer (Farinu & Baik, 2007). The convective boundary conditions i.e. heat and mass transfer coefficients vary during the frying process and depend on the frying parameters (Farinu & Baik, 2008). Several researchers have previously measured the convective heat transfer coefficient during frying for a variety of food products. In previous studies, heat transfer coefficient has been reported to rapidly increase as soon as the product is immersed in hot oil. Costa, Oliveira, Delaney, and Gekas (1999); Farinu and Baik (2007) and Hubbard and Farkas (1999) have reported that there is a rapid increase in the heat transfer coefficient during first 40 s of frying due to rapid evaporation and bubbling due to moisture loss. They found that the heat transfer coefficient attains a peak value during first 100 s of frying. During later stages of frying the evaporation subsides and heat transfer coefficient reduces to reach a plateau. Hubbard and Farkas (1999) also measured the convective heat transfer coefficient during frying of
potato cylinders. They reported the heat transfer coefficients to vary throughout the frying process, ranging from 300 W/m²K at the beginning of frying to 1100 W/m²K during middle stages of frying at 180 °C.

Three methods of measuring convective heat transfer coefficients during frying have been reported in literature, (a) steady-state measurement of surface temperature (no mass transfer), (b) transient measurement of temperature (uniform temperature assumption throughout the product undergoing frying), and (c) heat flux measurement of surface temperature (use of a sensor to measure heat flux at product surface) (Alvis, Vélez, Rada-Mendoza, Villamiel, & Villada, 2009; Mosavian & Karizaki, 2012). Costa et al. (1999) measured the heat transfer coefficient during frying by using a steel piece and a potato slice. They reported different heat transfer coefficients for both instances. They further stated that the differences were due to the bubbling during the potato slice frying and lack of it during the use of steel piece. Budžaki and Šeruga (2005) utilized the transient method to measure the convective heat transfer coefficients during frying of potato dough balls. They reported the heat transfer coefficients to increase with increasing frying temperature and stated that the composition of the dough resulted in change in heat transfer coefficients at similar frying temperatures. Most of the research further concludes that the heat transfer coefficient varies during the frying process and this variation is further due to the differences in frying temperature, type of frying oil, and food properties like size, shape, and initial moisture content. Also in most of the previous analysis of heat transfer coefficient, a constant value of oil temperature is assumed. This assumption holds when a low product to oil ratio is maintained. However,
this is not always true in an industrial frying setup where product to oil ratios are
comparably high and the introduction of moist product into the hot oil results in
decrease of frying oil temperature. Therefore, in order to fully elucidate the heat
transfer during a particular frying process, it is important to evaluate the heat transfer
coefficient during the frying process. Thus, in this particular study a real time oil
temperature profile was used to calculate the convective heat transfer coefficients using
a transient method of determination.

Convective boundary conditions employed in modeling of frying process are
influenced by the heat transfer coefficient (h). Heat transfer coefficient is one of the
major factors that govern the rate of heat and mass transfer during frying.
Therefore, the main objective of this study is to determine the heat transfer coefficient
during controlled 1D frying of a potato slice. In order to make the frying 1D a hollow
Teflon disc was used as a sample holder. The sample was fixated to the Teflon disc using
heat stable silicon glue. The heat transfer coefficient determined during this study will
be useful for modeling heat and mass transfer mechanisms during frying.

3.2. Materials and Methods

3.2.1 Frying experiments to determine convective heat transfer
coefficient

Frying experiments were performed using the Russet variety of potatoes.
Potatoes were peeled and sliced into thick discs (Thickness >> regular potato chips).
Discs of 1 cm thickness and 4 cm diameter were cut out from the thick discs with the
help of a stainless steel core cutter. Prepared discs were washed in cold water to
remove surface starch and were later patted using paper towels to remove any excess moisture.

Special hollow Teflon discs of 1 cm thickness and 4 cm internal diameter were designed to both serve as sample holder and insulator so that only top and bottom surfaces of potato discs were exposed to hot oil (Fig. 3.1). Three grooves of 0.1 mm diameter were made in the Teflon discs to serve as thermocouple carriers. Grooves were made at the center and 2.5 mm from top and bottom to maintain symmetry during temperature measurement. Although the discs fit tightly into the sample holder, thermo stable silicon glue was applied onto the potato disc side to prevent any oil seepage between the Teflon holder and potato disc edge. The silicon glue also helped in increasing the insulation efficiency of the Teflon sample holder and prevented samples from shrinking during frying.

Crisco brand of frying oil was used as the frying medium. A tabletop fryer (GE 12 cup deep fryer, GE, Bentonville, AR) of 3L capacity with temperature accuracy of ±2 °C was used. Constant product to oil ratio of 0.142 was maintained throughout the frying experiments. Oil was preheated for 60 min before frying to ensure homogeneous temperature distribution inside the fryer. Frying was conducted at three temperatures of 150, 170 and 190 °C. Oil was changed after a set of 5 frying trials.

When the food is immersed in hot oil, the heat is transferred from the hot oil to the potato disc. The total heat transferred from the hot oil via convection is utilized in sensible heating of the sample and evaporation of moisture to vapors. The heat transfer
coefficient at the surface can be estimated from the following equation (Farinu & Baik, 2007).

\[ hA(T_\infty - T_s) = MC_p \frac{dT}{dt} + \lambda \frac{dW}{dt} \]  \hspace{1cm} (2.1)

Where, \( h \) is the heat transfer coefficient, \( A \) is the surface area of the sample; \( T_\infty \) is the oil temperature, \( T_s \) is the surface temperature of the sample, \( M \) is the mass of the sample being fried, \( C_p \) is the specific heat capacity of the sample, \( dT \) is the change in the average temperature of the sample, \( \lambda \) is the latent heat of evaporation and \( \frac{dW}{dt} \) is the rate of moisture loss from the sample.

In order to determine the heat transfer coefficient from the above equation, the unknowns were determined from the experimental procedures.

- **Top and bottom sample surface area (\( A = \pi D^2/2 \)):** A potato disc of 4 cm diameter was cut using a metal corer. The disc diameter remained constant throughout the experimental procedure. Only top and bottom surfaces were exposed to the frying oil. Also, due to negligible shrinkage during frying, the surface area value remained constant at 25.12 \( \times \) 10\(^{-4} \) m\(^2\).

- **Sample Mass (\( M \)):** In order to prevent sample to sample weight variation due to variation in specific gravity, all disc samples were cut out from a single potato or from the same crosssection (in the center of the potato) in different potatoes. Similar technique was employed by Baumann and Escher (1995) to minimize sample to sample dry matter variation during frying of potato discs. The mass of discs was observed to be 13.166 \( \pm \) 0.5 \( \times \) 10\(^{-3} \) kg.
• **Specific Heat \((C_p)\):** Wang and Brennan (1993) evaluated the influence of moisture content and temperature on the specific heat of potatoes. They found the specific heat to increase with an increase in temperature and a decrease in moisture content. They proposed an equation relating specific heat with moisture content and temperature. Same relation was utilized to calculate the specific heat as a function of potato disc moisture content and temperature.

\[
C_p = 0.406 + 0.00146T + 0.203M - 0.0249M^2
\]  

(2.2)

Where, \(T\) is the real time average temperature of the sample in °C, \(M\) is the average moisture content (g water/g solid). Both, temperature and moisture content values were determined during the frying experiments. The above equation was input into Eq. (2.1) to determine the heat transfer coefficient.

• **Latent heat of evaporation \(\lambda\):** It was taken to be 2257 KJ/kg (Farinu & Baik, 2007)

• **Spatial Temperature distribution to determine \(T_s\), \(T_\infty\) and \(\frac{dT}{dt}\):** Frying was conducted to determine the spatial temperature distribution inside the potato discs. K-type thermocouples were inserted into the sample holder. Grooves of 1mm diameter and 20 mm length were made inside the potato discs by inserting needles through the guide holes in the sample holder and into the potato discs. The grooves ensured repeatable placement of thermocouples. This also made sure that temperature was measured at the same location during all replications. Surface temperature of potato discs was measured by placing thermocouples at the surface and fastening them using a c-clamp. Placement of thermocouples was investigated at the end of frying and those readings were discarded where the thermocouples
were found separated from the sample. The readings from the samples in which the silicon glue seeped out between the sample holder and sample were also discarded.

Average of top and bottom surface thermocouple readings was used as value for $T_s$. Similarly, average of thermocouple readings from middle, 2.5 mm from top and 2.5 mm bottom was taken and used as value for sample temperature to determine $\frac{dT}{dt}$ and $C_p$. Two thermocouples were also placed at two different locations inside the fryer. The two thermocouples were kept right above and below the samples to measure real time oil temperature. The average of the two readings was used as a value for $T_{\infty}$. Frying was conducted at 150, 170 and 190 °C. Six frying trials were conducted at each temperature and total frying time of 300 s was divided into 8 intervals of 0-20, 20-40, 40-60, 60-100, 100-150, 150-200, 200-250 and 250-300 s, respectively. An average heat transfer coefficient for each interval was calculated using Eq. (2.1).

- **Determination of drying rate ($\frac{dW}{dt}$):** Another set of frying experiments was conducted to measure the $\frac{dW}{dt}$ term in the heat balance equation. In these experiments it was not required to measure the temperature profiles inside the potato disc. However, the oil temperature was measured to ensure accurate frying conditions. Also, the product to oil ratio was kept consistent with previous experiments. In these experiments, frying was conducted on a weighing scale. It was assumed that loss in moisture of the product is the major factor contributing to weight loss during frying. The weight loss as a function frying time was measured by
recording the total system (fryer+oil+product) weight at 10-second intervals. As the weight of fryer is constant and the net oil content of the system does not change, the total loss in weight is same as loss in moisture of the system. Three frying iterations were conducted at each frying temperature of 150, 170 and 190 °C to calculate the drying rates.

3.2.2 Moisture and Fat Analysis

The frozen, powdered samples were analyzed for moisture content in an automatic moisture analyzer (MB35, OHAUS Corporation, Parsippany, NJ). The moisture meter was calibrated against hot air oven method (International, 1995). Frozen ground samples were prepared using grinder with each sample weighing about 0.5 grams. Powdered sample was spread thoroughly over the aluminum pans and placed over the pan support of moisture meter. Halogen element inside the moisture meter provided uniform infrared heating up to 160˚C in less than a minute. It heated the sample at a set temperature of 105˚C until the sample weight became constant. Moisture percentage as a function of weight change was recorded and displayed. The moisture content values measured by the moisture meter were converted to the oven-based values using the calibration curve.

Fat analysis was carried out using the modified Folch method based on total lipid determination (Iverson, Lang, & Cooper, 2001). All fat and moisture analysis was carried out in triplicates. The data was analyzed in MS Excel.
3.3. Results and Discussions

In the current experimental procedure, the potato discs are enclosed in Teflon holders. Thus, only top and bottom surfaces are exposed to the hot oil. This reduces the surface area available for moisture loss and heat transfer, which increases the frying duration. Fig. 3.2 depicts the heat transfer coefficient measured at 150, 170 and 190 °C, as a function of frying time. Overall, the heat transfer coefficient increases at a slower rate at 150 and 170 °C frying temperature. However, at 190 °C the rate of increase is rapid. This was in agreement with the findings of Farinu and Baik (2007) who also reported that the rate of increase in heat transfer coefficient was higher at higher frying temperature.

As the potato discs are immersed in hot oil, the heat transfer coefficient remains near constant at 150 and 170 °C till 100 s of frying time. However at 190 °C there is an immediate increase in the values of h. This results in higher surface temperature at 190 °C frying temperature at the beginning of frying (Fig. 3.3). As frying progresses beyond 100 s, there is an increase in the values of h. This increase is rapid at 190 °C frying temperature. An increase in h with an increase in frying temperature results in transfer of heat to the core of potato discs. This results in increase in temperature at the center and 2.5 mm from surface of potato disc. Higher temperatures were observed at greater frying temperatures (Figures 3.4 and 3.5).

Heat transfer coefficient attains the maximum value towards the end of frying for all the frying temperatures. This may be because the average surface temperature of the potato disc reaches closer to the temperature of the oil towards end of frying. The
maximum $h$ values, recorded during frying were 3617, 4517 and 7307 W/m$^2$°C at 150, 170 and 190 °C respectively. These values are higher than reported by Farinu and Baik (2007) and Baik and Mittal (2005) during previous frying of potato discs. They used a constant oil temperature by frying one potato disc at a time and keeping a low product to oil ratio. However, in the current study industrial frying conditions were employed and it was observed that the oil temperature varies by more than 15 °C during the course of frying. Therefore, a real-time oil temperature reading was taken near the product surface and was used as the time dependent oil temperature. The oil temperature dropped as frying progressed while, the product surface temperature increased. This resulted in high heat transfer coefficient values than reported previously in the literature.

Furthermore, as the heat transfer values increased with an increase in frying time and temperature, this promoted greater moisture loss with an increase in frying time and temperature (Fig. 3.6). Greater moisture loss was seen during frying at higher temperatures resulting in finished moisture values of 3.58, 2.97 and 2.57 (g/g solids) during frying at 150, 170 and 190 °C. However, as the frying temperature increased the average finished fat content decreased (statistically not significant, $p>0.05$). Final fat content values of 0.108, 0.102 and 0.094 were obtained during frying at 150, 170 and 190 °C.

### 3.4 Conclusions

The convective heat transfer coefficient was measured experimentally for obtaining heat transfer boundary conditions for mathematical modeling. The rate of
increase in the values of heat transfer coefficient increased with the increase in both frying time and temperature. The maximum \( h \) values, recorded during frying were 3617, 4517 and 7307 W/m\(^2\)\(^°\)C at 150, 170 and 190 °C respectively. High values of heat transfer coefficient resulted in greater internal temperature values \( (T_{\text{max, surface}} = 143, 147 \text{ and } 170 \degree C, T_{\text{max, 2.5 mm}} = 101.6, 102.9 \text{ and } 102.9, T_{\text{max, center}} = 101.4, 102.4 \text{ and } 103.3, \text{ at } 150, 170 \text{ and } 190 \degree C, \text{ respectively}) \), lower final moisture content \( (M_w = 3.11, 2.87 \text{ and } 2.61 \text{ decimal dry basis (ddb) at } 150, 170 \text{ and } 190 \degree C, \text{ respectively}) \). Towards the end of frying the surface temperature of potato disc approached the oil temperature. This resulted in peak heat transfer values towards the end of frying at all frying temperatures. Overall the product surface temperature remained 7-20 °C below the frying temperature (Oil temperature).
Fig. 3.1 Teflon sample holder with potato disc and thermocouples inserted
Fig. 3.2 Convective heat transfer coefficient as a function of frying time and temperature. Error bars indicate ± one standard error. Std. deviation range for the plot is: 5 to 576.36, number of replications per time point=5.
Frying Time (s)

Fig. 3.3 Surface temperature profiles during frying at 150, 170 and 190 °C
Fig. 3.4 Temperature profiles at 2.5 mm from surface of potato disc during frying at 150, 170 and 190 °C.
Fig. 3.5 Temperature profiles at center of potato disc during frying at 150, 170 and 190 °C.
Fig. 3.6 Average moisture content during frying at 150, 170 and 190 °C. Error bars indicate ± one standard error. Std. deviation range for the plot is: 0.03 to 0.35, number of replications per time point=3.
Chapter-4

Verification of Hybrid Mixture Theory Based Two-Scale Unsaturated Transport Processes Using Controlled Frying Experiments

4.1. Introduction

Deep fat frying has been defined as a cooking process in which, the food is immersed in edible oil heated to temperatures well above the boiling point of water (Bouchon, 2009). The frying process as a cooking mechanism is very popular especially among Americans with the annual spending on fried products exceeding $110 billion in year 2000. This figure is continuously increasing every year (Saguy & Dana, 2003). Although, the popularity of fried foods is continuously increasing due to the desirable texture (soft interior or core and crispy exterior or crust), the focus on reducing fat content of fried foods has also grown (Lalam, Sandhu, Takhar, Thompson, & Alvarado, 2013; Mir-Bel et al., 2009; Sandhu et al., 2013). In order to reduce the fat content of fried foods, it is critical to understand the frying process and the phenomena involved in oil uptake, moisture loss, texture development and heat transfer.

High temperatures and unsaturated transport (involvement of air-vapor mixture) makes it challenging to study frying by both experimental and modeling techniques. To study frying by physics based modeling, most experimental properties such as
diffusivity, permeability, water activity etc. are extrapolated to temperatures much higher than the range in which they were recorded. In addition, oil uptake is measured during post-process using Soxhlet technique, which records higher oil content than what penetrated the food due to movement of surface oil to inside during cooling. Due to these challenges, the involved mechanisms are still not fully understood despite a significant amount of research. A fundamental porous media physics based modeling approach combined with experimental techniques would serve as a viable technique for understanding the mechanisms, optimizing the process and improving the quality of fried foods.

Several researchers have described the heat and mass transfer occurring in frying via mathematical modeling and computer simulations (Farinu & Baik, 2008; Moreira & Barrufet, 1996; Ni & Datta, 1999; Yamsaengsung & Moreira, 2002b) and also by measuring change in properties of fried foods as a function of frying time and frying temperature through experimental techniques (Alvis et al., 2009; Gamble & Rice, 1988). Ni and Datta (1999) developed a model for frying of a potato slab. They described the moisture, and oil transport during frying utilizing the diffusion, capillary flow and convective flow porous media equations.

Attempts to elucidate the physics of frying process using mathematical modeling have been made in the past. Farkas, Singh, and Rumsey (1996) developed a single-scale mathematical model to describe the heat and mass transfer during frying of a potato mixture. Whitaker (1977) studied simultaneous transfer of heat, mass and momentum in porous media using the concepts of pressure driven flow and volume
averaging during drying. Using similar approach to Whitaker (1977), Halder et al. (2007b) and Ni and Datta (1999) developed transport equations and solved them to study the frying process. In the present study the frying problem has been studied using the two-scale hybrid mixture theory (HMT) based unsaturated transport equations developed by Takhar (2014). HMT involves hybridization of the mixture theory with upscaling techniques (Cushman, 1997). At microscale (scale of biopolymers), laws of conservation of mass, momentum, energy and entropy are upcaled to meso (scale of cell cytoplasm) and macroscales (tissue scale) using volume averaging. At macroscale, the constitutive theory is formulated and entropy inequality is exploited to obtain resulting equilibrium, near-equilibrium and non-equilibrium relations. Recently, Takhar (2014) used HMT to obtain unsaturated transport relations for biopolymers that can be used to predict transport mechanisms and thermomechanical changes in foods.

Bansal, Takhar, and Maneerote (2014) used HMT based equations to simulate frying of rice crackers and obtained good results. A similar approach is adopted in the present study to simulate the frying of potato discs. In the past HMT based frying study the model predicted moisture content and temperature accurately, but under predicted the experimental oil content. It is expected that experiments resulted in higher oil content measurement due to penetration of surface oil during cooling stage. Therefore, in the current study, model validation is performed by making comparison between predicted and experimental oil content values after removing the surface oil, which was expected to have penetrated during post-process cooling. In addition, HMT based equations are tested in a controlled one-dimensional flow; which is expected to provide
a better estimate of oil, moisture and temperature profiles than three-dimensional flow.
The temperature data is also obtained at different locations to facilitate model validation. HMT based equations are solved using finite element method to obtain profiles for moisture, temperature and oil content.

4.2. Hybrid Mixture Theory Based Model Representing the Frying Process

Fried potato products are porous in nature, and consist of solid matrix, liquid water, water vapor, air and oil. The transport processes inside the fried potato products are described using a multiphase porous media model. The transport equations are solved for liquid water, oil and gas phase. Two scale equations for conservation of mass, momentum and energy are solved.

The velocity ($v^{\alpha,s}$) of a fluid phase ($\alpha = w, o, g$) relative to the solid phase (s) is given by the generalized Darcy’s Law (Takhar, 2014):

$$v^{\alpha,s} = -\varepsilon^\alpha \frac{K^\alpha}{\mu^\alpha} \nabla p^\alpha - \varepsilon^\alpha D^\alpha \nabla \varepsilon^\alpha - \frac{\varepsilon^\alpha D^\alpha}{E^\alpha} \nabla \varepsilon^\alpha,$$  \hspace{1cm} (2.1)

The first term on the right hand side (RHS) of this equation refers to pressure gradient driven flow and the second term accounts for the flow due to concentration gradient. The last term on the RHS accounts for viscous resistance of the polymeric matrix to fluid flow.

The permeability, viscosity, diffusivity and elasticity of a fluid phase are interrelated (Achanta, 1995):
The upscaled generalized mass balance equation for fluids was stated by Takhar (2014) as:

\[ \frac{D^\alpha}{Dt} + \nabla \cdot (\varepsilon^\alpha \nu^\alpha, \rho^\alpha) - \frac{\varepsilon^\alpha}{\varepsilon^s} \dot{\varepsilon}^s \rho^\alpha = \sum_{\beta \neq \epsilon} \beta \dot{\varepsilon}^\alpha, \text{ where } (\alpha = w, o, g) \quad (2.3) \]

The general transport equations for mass transfer are obtained by substituting \( \nu^\alpha, \varphi \) from (2.1) into (2.3). The transport equations for different fluid phases thus obtained are given as follows,

Water phase:

\[ \frac{D^s(\varepsilon^w)}{Dt} - \nabla \cdot \left( (\varepsilon^w)^2 \left( \frac{K^w}{\mu^w} \nabla \rho^w + \frac{D^w}{E} N^w \nabla \frac{D^s(\varepsilon^w)}{Dt} \right) \right) + \varepsilon^w \frac{\phi}{1 - \phi} = - \frac{1}{\rho^w} \varepsilon^w \varphi \quad (2.4) \]

Oil phase:

\[ \frac{D^s(\varepsilon^o)}{Dt} - \nabla \cdot \left( (\varepsilon^o)^2 \left( \frac{K^o}{\mu^o} \nabla \rho^o + \frac{D^o}{E} N^o \nabla \frac{D^s(\varepsilon^o)}{Dt} \right) \right) + \varepsilon^o \frac{\phi}{1 - \phi} = 0 \quad (2.5) \]

Gas phase:

\[ \frac{D^s(\varepsilon^g)}{Dt} - \nabla \cdot \left( (\varepsilon^g)^2 \rho^g \frac{K^g}{\mu^g} \nabla \rho^g \right) + \varepsilon^g \rho^g \frac{\phi}{1 - \phi} = \varepsilon^g \quad (2.6) \]

The solid volume fraction \( \varepsilon^s \) is related to porosity \( \phi \) by:

\[ \varepsilon^s = 1 - \phi, \text{ where, } \phi = \varepsilon^o + \varepsilon^w + \varepsilon^g. \]

The conversion of water to vapors during frying implies that the gas phase constitutes of air and water vapors. As gas phase follows Dalton’s law of partial pressure (2.6) can be modified to obtain mass balance equation for vapor phase. This can be
achieved by exploiting ideal gas law to determine vapor pressure. The vapor-mass balance and diffusion equations are utilized to determine the density of vapors as,

$$\frac{D\varepsilon\rho v}{Dt} = \nabla \cdot (\varepsilon v \rho v v \nabla) + \frac{\phi}{1-\phi} \varepsilon v \rho v = \frac{w}{\delta}$$

(2.7)

In order to account for the porosity, mass balance for solid biopolymers is invoked. The relationship between porosity and volume fraction can be obtained as,

$$\frac{D\phi}{Dt} - (1 - \phi)\nabla \cdot v = 0$$

(2.8)

To calculate the transfer of heat energy, heat balance equation of de Vries (1958) is solved along with the mass transport for different fluids.

$$\rho C_p \frac{\partial T}{\partial t} + \sum_{\alpha=w, \rho, g} \rho^\alpha C_p^\alpha \nabla T \cdot v^\alpha = \nabla \cdot (k \nabla T) - \lambda w \hat{e}^g$$

(2.9)

In modeling single scale problems the source/sink term, $w \hat{e}^g$ is usually missing. However, for multiscale modeling problems like frying, this term is of great significance as it helps in coupling water and water vapor phase mass balance equations. This coupling is crucial to conserve liquid and vapor phase mass. The rate of phase change can be calculated as,

$$w \hat{e}^v = w \hat{e}^g = \xi \ln\left(\frac{\rho^v}{\rho^g}\right)$$

(2.10)

The above equation was developed by Takhar (2014) using continuum thermodynamics. It utilizes the HMT based relation, which states that the difference between Gibbs free energies of two different states of a fluid drives phase change. Here $\xi$ represents the evaporation rate constant. The evaporation rate constant depends on the material and process parameters and an increase in its value indicates an
increase in rate of evaporation (Bansal et al., 2014). The relationships required to solve the above equations are given in Table 4.2.

**4.2.1 Initial and Boundary Conditions**

The initial moisture content of potatoes was measured to be 5.45 g/g solids. The following equation was used to relate the moisture content of potatoes with the volume fractions

\[ \varepsilon_i^w = \frac{W_{w,i} \rho_s (1 - \varepsilon_i^g - \varepsilon_i^o)}{\rho^w + W_{w,i} \rho_s} \] (2.11)

The initial volume fraction of gas phase \( \varepsilon_i^g \) was estimated inversely to be 0.1. Although, the potatoes have miniscule amount of initial oil content, the initial volume fraction of oil phase \( \varepsilon_i^o \) was assumed to be 0.0001. This value was used to avoid numerical oscillations during simulations.

Using the above values in (2.11), \( \varepsilon_i^w = 0.793 \) for Eq. (2.4).

For Eq. (2.5), \( p_i^g = P_{atm} \) and \( \rho_i^v = \frac{p_{eq,i}^v}{R v T_i} \) for Eq. (2.6). Also, initial porosity, \( \phi_i \), is estimated as,

\[ \phi_i = \varepsilon_i^w + \varepsilon_i^g + \varepsilon_i^o = 0.8931 \], and the initial temperature for Eq. (2.9) was, \( T_i = 298K \).

For the solution of transport equations for water, vapor, oil and heat, Neumann boundary conditions were employed as,

\[ Q_{mw} = h_{mw} (\varepsilon_i^w - \varepsilon^w) \] for water phase Eq. (2.4) (2.12)

\[ Q_{mo} = h_{mo} (\varepsilon_i^o - \varepsilon^o) \] for oil phase Eq. (2.5) (2.13)

\[ Q_{mv} = h_{mv} (P_i^v - P^v) \] for vapor phase Eq. (2.7) (2.14)

\[ Q_{heat} = h (T_{oil} - T) \] for heat balance Eq. (2.9) (2.15)
Also, at the boundary (interface of oil and potato sample) the gas pressure is same as atmospheric pressure \( (P^g_s = P_{atm}) \). Furthermore, the oil volume fraction \( (\epsilon_{oil}^o) \) in the bulk oil-phase is 1. The supporting relationships and material properties for boundary conditions are given in Table 4.3.

### 4.2.2 Numerical Solution for Equations

The equations were solved using Comsol Multiphysics (Comsol Inc., Burlington, MA), a commercial finite element software package. Mapped mesh was used to create a 22-element distribution inside a 2-D axisymmetric potato slice (Fig. 4.1, radius = 20 mm, thickness = 5 mm). A time-dependent MUMPS solver was employed with a memory allocation factor of 1.2 and a time step of 0.1 s to obtain solution of the model.

Simulations were carried out on a MacBook Pro with 2.4 GHz Intel Core 2 Duo processor system with a 4 GB RAM. Each simulation run took approximately 15 minutes to complete for a frying process time from 0 to 300 s.

### 4.2.3 Experimental Procedures

Frying experiments were performed using the Russet variety of potatoes.

Potatoes were peeled and sliced into thick discs. Discs of 1 cm thickness and 4 cm diameter were cut out from the thick discs with the help of a stainless steel core cutter. Prepared discs were washed in cold water to remove surface starch and were later patted using paper towels to remove any excess moisture.

Special hollow Teflon discs of 1 cm thickness and 4 cm internal diameter were designed to both serve as sample holder and insulator so that only top and bottom surfaces of potato discs were exposed to hot oil (Fig. 4.2). This served as a simplification
step for frying model solution. Three grooves of 0.1 mm diameter were made in the Teflon discs to serve as thermocouple carriers. Grooves were made at the center and 2.5 mm from top and bottom to maintain symmetry during temperature measurement. Potato discs were placed in the Teflon holder. Although the discs fit tightly into the sample holder, thermo stable silicon glue was applied onto the potato disc side to prevent any oil seepage between the Teflon holder and potato disc edge. The silicon glue also helped in increasing the insulation efficiency of the Teflon sample holder.

Crisco brand of oil was used as the frying medium. A tabletop fryer of 3L capacity with temperature accuracy of ±2 °C was used. Constant product to oil ratio of 0.142 was maintained throughout the frying experiments. Oil was preheated for 60 min before frying to ensure homogeneous temperature distribution inside the fryer. Frying was conducted at three temperatures of 150, 170 and 190 °C. Oil was changed after a set of 5 frying trials. Six frying trials were conducted at each temperature and total frying time of 300 s was divided into 8 intervals of 0-20, 20-40, 40-60, 60-100, 100-150, 150-200, 200-250 and 250-300 s, respectively.

4.2.4 Determination of Spatial Temperature Profiles

Frying was conducted to determine the spatial temperature distribution inside the potato discs. K-type thermocouples were inserted into the sample holder. Grooves of 1mm diameter and 20 mm length were made inside the potato discs by inserting needles through the guide holes in the sample holder and into the potato discs. The grooves ensured repeatable placement of thermocouples. This also made sure that temperature was measured at the same location during all replications. Surface
temperature of potato discs was measured by placing thermocouples at the surface and fastening them using a c-clamp. Placement of thermocouples was investigated at the end of frying and those readings were discarded where the thermocouples were found separated from the sample. The readings from the samples in which the silicon glue seeped out between the sample holder and sample were also discarded. Two thermocouples were also placed at two different locations inside the fryer. The two thermocouples were kept right above and below the samples to measure real time oil temperature.

4.2.5 Moisture and Fat Analysis

The frozen, powdered samples were analyzed for moisture content in an automatic moisture analyzer (MB35, OHAUS Corporation, Parsippany, NJ). Moisture meter was calibrated against hot air oven method (AOAC, 1996). Frozen ground samples were prepared using a grinder with each sample weighing about 0.5 grams. Powdered sample was spread thoroughly over the aluminum pans and placed over the pan support of moisture meter. Halogen element inside the moisture meter provides uniform infrared heating up to 160°C in less than a minute. It heats the sample at a set temperature of 105°C until the sample weight becomes constant. Moisture percentage as a function of weight change was recorded and displayed. The moisture content values measured by the moisture meter were converted to the oven-based values using the calibration curve.

Fat analysis was carried out using the modified Folch method based on total lipid determination. All fat and moisture analysis was carried out in triplicates.
4.2.6 Surface Oil Removal

The experimental values of total fat content tend to be higher than actual values of fat inside the food product. This is due to formation of a thin layer of surface fat once the fried potato discs are removed from the hot oil (Bouchon, Hollins, Pearson, Pyle, & Tobin, 2001). This causes large differences between simulated and experimental values of fat content. In order to remove surface oil, procedure adopted by Pedreschi and Moyano (2005) and Bouchon and Pyle (2005) was used. After frying, the discs were immediately transferred to a beaker containing petroleum ether. After a residence time of 10 s the discs were removed and kept on a filter paper inside an air oven at 110 °C for 20 minutes to remove excess solvent. The fat content of the whole slice was then measured using procedure described in section 2.5.

4.2.7 Data Analysis

The experimental and simulated data was analyzed using MS Excel. ANOVA procedure was used to determine significant differences between experimental and simulated data. SAS software version 9.3 (SAS Institute Inc., Cary, NC) was used to carry out the ANOVA procedure at significance level of 0.05.

4.3. Results and Discussions

4.3.1 Comparison of Experimental and Predicted Data

Experimental temperature, moisture loss and fat uptake profiles plotted as a function of frying time and temperature are compared with predicted profiles as discussed below.
The moisture content and oil content predicted using the simulations at different frying temperature and time were averaged on volume basis. The following equation was used to carry out volume averaging for moisture content:

\[ W_{w,avg} = \frac{\int W_w dV}{\int dV} \]  

(3.1)

A similar equation was used to obtain average oil content on volume basis.

Percent average absolute difference (AAD) \( (\frac{1}{n} \sum_{j=1}^{n} \frac{|X_{pred,j} - X_{exp,j}|}{X_{exp,j}} \times 100) \) was used to determine the agreement between the experimental and predicted values for temperature, moisture content and oil content.

### 4.3.2 Temperature Profiles inside Potato Disc

Temperature inside the potato discs was measured at the surface, 2.5 mm from the surface and 5 mm from the surface (center) using K-type thermocouples during frying. The experimental temperature values were compared with the values calculated using simulations.

Fig. 4.3 depicts the calculated spatial temperature distribution inside the potato disc during frying at 170 °C. It can be seen that throughout the frying period, the surface temperature remained well above the temperatures in the interior of potato disc. As the potato disc is immersed in hot oil, the convective heat from the hot oil results in rapid increase of surface temperature. As a result the surface temperature approaches the oil temperature. As frying progresses, the heat is transferred towards the interior regions through conduction and convection.
However, as the potato disc is high in initial moisture content (5.46 g/g solids), the surface moisture flashes off within a few s of frying. This rapid removal of surface moisture results in evaporative cooling and slight decrease in the surface temperature. Farkas et al. (1996) also reported similar dip in the surface temperature during the frying of potato discs and found the dip to be proportional to frying temperature. The slight decrease in surface temperature at the beginning of frying was observed after 50, 30 and 20 s of frying at 150, 170 and 190 °C respectively. The surface temperature continued to increase as frying progressed till 150 s. Beyond 150 s, the surface temperature dropped due to evaporative cooling and increased bubbling, which was observed experimentally due to migration of moisture from the interior of the potato disc to the surface. As frying progressed further, surface temperature remained constant until the end of frying indicating a constant surface evaporation throughout the frying period. The surface temperature, on an average, remained 15 °C below the frying temperature throughout the frying process.

The temperature in the interior of the potato disc increased at a slower rate than at the surface and remained well below the frying temperature throughout the frying. However, the maximum temperature in the interior of the potato disc increased with an increase in frying temperature and an increase in distance from the center of the potato disc. As frying progressed the rate of increase of internal temperature decreased due to decrease in thermal gradient across the potato slice. It is important to note that till 150 s, the temperature in the interior of potato disc (center to 3 mm) remained below 100 °C. This is because, high amount of moisture in the core prevents the temperature to go
Beyond 100 °C. In comparison, temperatures in the outer region of the potato disc (3 mm to 5 mm) were observed to go beyond 100 °C. This was supported by the fact that the outer surface loses most of the moisture, allowing greater temperature in solid biopolymers due to heat penetration by conduction and penetration of high temperature oil to the surface layers.

Beyond 150 s, the temperatures in the interior increased above 100°C indicating the movement of the evaporation front towards the interior of the potato disc. Towards the end of frying, the temperatures remained nearly constant but well above the boiling point of water, which indicates reduced cooling effect due to loss of moisture.

Figures 4.4, 4.5 and 4.6 depict the temperature profiles (experimental and predicted) at the surface, 2.5 mm and center of the potato disc during frying at 150, 170 and 190 °C, respectively. There was a good agreement between the experimental and predicted temperature profiles and the model predicted the temperature inside the potato discs with the sufficient accuracy. However, the accuracy of the model decreased as the frying temperature increased. An AAD of 10, 12 and 20 % between the predicted and experimental values was observed at 150, 170 and 190 °C, respectively.

4.3.3 Moisture Profiles

Fig. 4.7 depicts the spatial moisture distribution inside the potato disc during frying at 170 °C. As evident from the temperature profiles discussed in the previous section, the surface temperature of the potato discs reaches the boiling point of free water almost instantaneously after immersion in the frying oil which is in agreement with Vitrac et al. (2000). This results in surface moisture flash off and superficial boiling.
As a consequence, the moisture loss from the surface is rapid during the first 60 s of frying. This fact is further supported by extremely high evaporation rates observed near the surface during the initiation of frying. Maximum evaporation rate of 0.32 kg/m$^3$s was observed near the surface of potato slice at 60 s frying time (Fig. 4.8). As frying progresses, the moisture from the interior is transferred to the surface via diffusion and pressure driven flow, where it is lost due to evaporation. As the internal temperature of the potato discs increases, there is continuous decrease in moisture content of potato discs as a function of frying time, albeit at a much slower rate. This is due to the decreased evaporation rates observed as frying progresses beyond 60 s.

Fig. 4.9 depicts the moisture loss profiles as a function of frying time during frying at 150, 170 and 190 °C respectively. The dotted lines in the figure represent the predicted moisture content values. The percent AAD between the predicted and experimental moisture content was less than 5.7% at the three frying temperatures and indicates a good agreement between the experimental and predicted values.

4.3.4 Oil Uptake Profiles

Oil uptake is a complex phenomenon and the fried food industry constantly struggles to reduce fat content of fried foods. Oil uptake not only affects the taste and flavor but also the crispiness and texture of the fried foods. As discussed earlier, the use of Teflon holder reduces the surface area exposed to the oil. This resulted in reduced moisture loss. Sandhu et al. (2013) stated that during the frying of potato discs, reduced moisture loss rates result in lesser internal pressure development and reduced oil uptake rates. Fig. 4.10 depicts the spatial oil distribution inside the potato disc during
frying at 170 °C. It is important to note that most of the oil uptake occurs only near the surface and oil only penetrated to 0.25 mm inside the potato disc. This may be due to the fact that the Teflon sample holder insulates the edges and reduces the surface area available for oil uptake. As frying progressed, the surface oil content increased and maximum oil content of 1.6 (g/g solids) was observed at the end of frying. The major factor resisting oil movement towards the interior of frying is the development of gas pressure due to evaporation of water (Sandhu et al., 2013).

As frying time increased beyond 60 s, a slight dip in fat content values was observed near the surface. This may be due to removal of absorbed oil by outgoing moisture resulting in reduced oil content values. At longer frying times, some oil penetration was observed but no oil penetration was seen beyond 0.25 mm.

Fig. 4.11 depicts the comparison between the experimental and predicted fat uptake profiles at 150, 170 and 190 °C. As evident from the profiles, there is a substantial difference between the experimental and predicted fat uptake values. The Average Absolute difference of 88, 119 and 91% was observed between simulated and experimental oil content values at 150, 170 and 190 °C respectively. This is due to the fact that as the fried food is pulled out from the fryer, a thin film of oil forms on the exposed surface of potato discs. This thin film of oil increases the experimental fat content values. However, the model only accounts for penetrated oil. This results in differences between predicted and experimental fat content values. Similar observations were noted by Bouchon et al. (2001).
To account for surface oil penetration, another set of experiments was performed, where, surface oil was removed from the fried potato discs by immersing them in petroleum ether for 10 s. Similar procedure was used by Pedreschi and Moyano (2005) to remove the surface oil. Residence time of 10 s was chosen as longer residence times might result in removal of absorbed fat. Removal of surface oil further resulted in better agreement between the predicted and experimental fat content values (Fig. 4.12). Better agreement was observed for first 200 s of frying. Beyond 200 s the AAD between the predicted and experimental values increased. Overall, AAD of 14, 31 and 20 % was observed between predicted and experimental values at 150, 170 and 190 °C respectively. This level of accuracy was expected for oil uptake prediction, as the diffusive values of oil and other transport properties are also not known precisely at frying temperatures.

The simulations indicated that most of the oil uptake occurred during the first 100 s during frying at 170 and 190 °C. At 150 °C frying temperature the oil uptake rates were slower but fat uptake continued towards the end of frying. Lower frying temperature resulted in higher final fat content (0.039 g/g solids at 150 °C and 0.023 g/g solids at both 170 and 190 °C). Higher frying temperature may have resulted in faster formation of surface crust. The faster formation of surface crust may have hindered the oil uptake, which resulted in reduced oil uptake and less finished oil content at 170 and 190 °C.
4.3.5 Pressure Profiles

As the frying oil heats the food product, the moisture in the food is transformed into vapors. The vapors result in increase in gas pressure and offer resistance to oil uptake. Furthermore, oil uptake is a pressure driven phenomenon, which is mediated by capillary forces (Bouchon & Pyle, 2005). In order to fully understand the complex phenomena of oil uptake it is critical to investigate the pressure changes in the interior of food products undergoing frying.

Pore pressure was calculated using: \( p_{pore} = (P^wS^w + P^gS^g + P^0S^0) \) (Ehlers & Bluhm, 2002). The pore pressure represents the effective pressure exerted by various fluids on the pore walls. These fluids include oil, gas (vapor-air mixture) and water. Figures 4.13, 4.14, 4.15 and 4.16 represent the calculated spatial pore pressure, gas pressure, capillary pressure and water pressure profiles inside the potato disc during frying at 170 °C, respectively.

Potatoes are starchy foods with high initial moisture content and rigid cell walls that can withstand increase in internal pressure. Fig. 4.15 shows that the water-gas capillary pressure at the surface increases beyond atmospheric pressure during frying. This results in water pressure becoming positive up to 60 s (Fig. 4.16). As a result pore pressure also becomes positive upto 60 s frying. In the interior of potato disc, the capillary pressure remains close to the atmospheric pressure. This coincides with an increase in water pressure in the interior of potato disc until 60 s of frying (5x10^5 Pa). This results in extension of positive pore pressure towards the interior of the potato slice. Similar trend is seen in the profile of gas pressure (Fig. 4.14). Important point to
note is that, all this is in agreement with the increased surface evaporation rate near the surface of potato disc which attains a peak at 60 s (Fig. 4.8). Positive gas pressure and pore pressure are expected to resist oil penetration up to 60 s frying at 170 °C. For frying at 150 and 190 °C temperature peak positive gas and pore pressure values were also observed at 60 s frying time. The maximum evaporation rate was observed at 60 s and 40s for frying at 150 and 190 °C, respectively (data not shown).

Beyond 60 s of frying, the increase in capillary pressure is seen towards the interior of potato slice (only till 0.001 mm into the surface). This results in drop in water pressure to negative values (Fig. 4.16). The negative trend in water pressure profile results in negative pore pressure values (Fig. 4.13). This is due to the fact that as the internal temperature increases, starch gelatinization results in tissue softening. The softened tissue is no longer able to hold the pressure due to conversion of water-to-water vapor. This results in an immediate drop in internal pressure, thus resulting in reduced gas pressure. In addition, increase in capillary pressure in hydrophilic matrix due to reduction in water content makes water pressure negative ($p^w = p^g - p^c$). Negative water pressure results in negative pore pressure. This may have allowed the oil to penetrate into the interior of potato disc after 60 s of frying. This is in agreement with the experimental findings of Sandhu et al. (2013) for frying of potato discs. In the frying literature, the role of oil capillary pressure in causing oil uptake has been discussed. Here we note that the water-air capillary pressure also plays a very important role in affecting oil uptake due to its influence on pore pressure.
However, the fact that gas pressure remained above the atmospheric pressure throughout the frying may have limited the oil penetration towards the interior of the potato discs to only 0.25 mm into the potato slice. Thus reducing the magnitude of negative pore pressure by maintaining positive gas pressure in the interior of potato slice may help in reducing the oil uptake during frying. This may require changing how the potato slice looses moisture during frying. Furthermore, controlling the time the potato slice is exposed to the negative pore pressure periods during frying will also help in reducing the oil uptake. After the fried potatoes are taken outside the fryer, surface oil stripping or drainage operations need to be conducted immediately as the oil may penetrate deeper inside the matrix due to negative pore pressure. This was also observed experimentally by Sandhu et al. (2013).

4.4 Conclusions

A good agreement between the predicted and experimental values of temperature, moisture loss and fat uptake profiles at all frying temperatures validated the frying model. Positive gas pressure values throughout the frying in the interior of potato disc, due to low water pressure, rendered the oil uptake to be a surface phenomenon. Which was in agreement with the experimental findings of Sandhu et al. (2013). Simulations also showed that oil penetrated to only 0.25 mm into the potato disc. Pore pressure remained negative beyond 60 s frying time for frying at 150, 170 and 190 °C, which may act as a driving force for oil uptake resulting in slight penetration of oil into the potato disc. The range of pore pressure was between -0.2 to 0.4 MPa. Removal of surface oil, which was expected to have penetrated potatoes during the
post-process cooling, resulted in improved prediction of experimental oil content values. Percentage Average Absolute Difference (AAD) between predicted and experimental values for moisture content was 3.89%, 5.7% and 5.5% and oil content was 14%, 31% and 20% at 150, 170 and 190 °C respectively. Maximum evaporation rate of 0.32 kg/m$^3$/s was observed near the surface of potato slice at 60 s frying time resulting in rapid moisture loss. Higher evaporation rates near the surface resulted in greater moisture loss while the interior remained high in moisture content even towards the end of frying.
Table 4.1. Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$</td>
<td>Porosity</td>
</tr>
<tr>
<td>$\dot{\phi}$</td>
<td>Time derivative of porosity ($s^{-1}$)</td>
</tr>
<tr>
<td>$\varepsilon^\alpha$</td>
<td>Volume fraction of phase</td>
</tr>
<tr>
<td>$\dot{\varepsilon}^\alpha$</td>
<td>Time derivative of volume fraction of phase ($s^{-1}$)</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature (K)</td>
</tr>
<tr>
<td>$K^\alpha$</td>
<td>Permeability ($m^2$)</td>
</tr>
<tr>
<td>$\mu^\alpha$</td>
<td>Dynamic viscosity (Pa.s)</td>
</tr>
<tr>
<td>$\rho^\alpha$</td>
<td>Mass exchange from one phase to another (kg/m³ s)</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Density (kg/m³)</td>
</tr>
<tr>
<td>$C_p^\alpha$</td>
<td>Evaporation rate constant (kg/m³ s)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Heat capacity (J/kg K)</td>
</tr>
<tr>
<td>$D^\alpha$</td>
<td>Diffusivity of fluid phase into polymeric matrix ($m^2$ s)</td>
</tr>
<tr>
<td>$D^{\alpha\beta}$</td>
<td>Diffusivity of one phase into another</td>
</tr>
<tr>
<td>$N^\alpha$</td>
<td>Mixture viscosity (Pa-s)</td>
</tr>
<tr>
<td>$E$</td>
<td>Modulus of elasticity (Pa)</td>
</tr>
<tr>
<td>$a_w$</td>
<td>Water activity</td>
</tr>
<tr>
<td>$p^\alpha$</td>
<td>Pressure (Pa)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Latent heat of vaporization (J/kg)</td>
</tr>
<tr>
<td>$\nu^\alpha$</td>
<td>Velocity of solid phase for matrix expansion (m/s)</td>
</tr>
<tr>
<td>$\nu^{\alpha,s}$</td>
<td>Velocity of $\alpha$ fluid phase wrt solid phase (m/s)</td>
</tr>
<tr>
<td>$K^\alpha$</td>
<td>Thermal conductivity (W/mK)</td>
</tr>
<tr>
<td>$h$</td>
<td>Heat transfer coefficient (W/m³K)</td>
</tr>
<tr>
<td>$h_{nv}$</td>
<td>Mass transfer coefficient for vapor phase (m/s)</td>
</tr>
<tr>
<td>$h_{nw}$</td>
<td>Mass transfer coefficient for water phase (m/s)</td>
</tr>
<tr>
<td>$R_v$</td>
<td>Specific gas constant for water vapors (J/kg K)</td>
</tr>
<tr>
<td>$R_g$</td>
<td>Specific gas constant for air (J/kg K)</td>
</tr>
<tr>
<td>$W_w$</td>
<td>Moisture content (g water/g solids)</td>
</tr>
<tr>
<td>$p^g$</td>
<td>Capillary pressure (Pa)</td>
</tr>
<tr>
<td>$R_{pore}$</td>
<td>Average radius of pores (m)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of contact (°)</td>
</tr>
<tr>
<td>$M^\alpha$</td>
<td>Molecular weight (kg/mol)</td>
</tr>
<tr>
<td>$x^\alpha$</td>
<td>Mole fraction</td>
</tr>
<tr>
<td>$S^\alpha$</td>
<td>Degree of saturation</td>
</tr>
<tr>
<td>$D$</td>
<td>Material derivative of a variable with respect to velocity of the solid phase</td>
</tr>
<tr>
<td>$\nabla$</td>
<td>Del operator</td>
</tr>
<tr>
<td>$j^s$</td>
<td>Jacobian operator for solid phase</td>
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Table 4.1 (Cont.)

<table>
<thead>
<tr>
<th>Superscripts</th>
<th>Nomenclature</th>
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<tr>
<td>α</td>
<td>General representation of phase</td>
</tr>
<tr>
<td>β</td>
<td>Phase other than α</td>
</tr>
<tr>
<td>a</td>
<td>Air</td>
</tr>
<tr>
<td>v</td>
<td>Water vapor phase</td>
</tr>
<tr>
<td>g</td>
<td>Gas phase</td>
</tr>
<tr>
<td>w</td>
<td>Water phase</td>
</tr>
<tr>
<td>o</td>
<td>Oil phase</td>
</tr>
<tr>
<td>s</td>
<td>Solid phase</td>
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<table>
<thead>
<tr>
<th>Subscripts</th>
<th>Nomenclature</th>
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<tr>
<td>atm</td>
<td>Atmosphere</td>
</tr>
<tr>
<td>avg</td>
<td>Average</td>
</tr>
<tr>
<td>exp</td>
<td>Experiment</td>
</tr>
<tr>
<td>eq.</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>i</td>
<td>Initial</td>
</tr>
<tr>
<td>max</td>
<td>Maximum</td>
</tr>
<tr>
<td>oil</td>
<td>Oil side</td>
</tr>
<tr>
<td>pred</td>
<td>Predicted</td>
</tr>
<tr>
<td>s</td>
<td>Surface</td>
</tr>
<tr>
<td>sat</td>
<td>Saturated</td>
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### Table 4.2, Material Properties

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<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
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<tbody>
<tr>
<td><strong>Density ($\rho$) kg/m$^3$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>838.466135+1.400506T+0.0030112376T$^2$+3.718223137×10$^{-7}$T$^3$</td>
<td>(Poling, Prausnitz, &amp; O’Connell, 2001)</td>
</tr>
<tr>
<td>Air</td>
<td>Ideal Gas</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>1106.11-0.64T</td>
<td></td>
</tr>
<tr>
<td><strong>Specific Heat ($C_p$) J/kg/K</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid</td>
<td>1360</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>12010.14-80.40T+0.31T$^2$-5.38×10$^{-7}$T$^3$+3.62×10$^{-17}$T$^4$</td>
<td>(Zabransky, Vlastimil Ruzicka, &amp; Domalski, 2001)</td>
</tr>
<tr>
<td><strong>Elasticity (E) Pa</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor</td>
<td>1.0763-0.37T+0.45×10$^{-4}$T$^2$-0.60×10$^{-1}$T+1.28×10$^{-10}$T$^4$</td>
<td>(Poling et al., 2001)</td>
</tr>
<tr>
<td>Air</td>
<td>1.28×10$^{-3}$×10$^{-7}$T+1.18×10$^{-10}$T$^4$</td>
<td>(Poling et al., 2001)</td>
</tr>
<tr>
<td>Oil</td>
<td>1.87×10$^{-2}$×10$^{-9}$T+1.54×10$^{-12}$T$^2$</td>
<td>(Zabransky et al., 2001)</td>
</tr>
<tr>
<td>**Dynamic Viscosity ($\mu$ Pa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vapor</td>
<td>-0.12×10$^{-6}$×3.83×10$^{-1}$T+3.85×10$^{-12}$T$^2$+2.10×10$^{-11}$T$^3$</td>
<td>(Varganahik, 1975)</td>
</tr>
<tr>
<td>Air</td>
<td>-0.12×10$^{-6}$×3.83×10$^{-1}$T+3.85×10$^{-12}$T$^2$+2.10×10$^{-11}$T$^3$</td>
<td>(Varganahik, 1975)</td>
</tr>
<tr>
<td>Oil</td>
<td>-0.12×10$^{-6}$×3.83×10$^{-1}$T+3.85×10$^{-12}$T$^2$+2.10×10$^{-11}$T$^3$</td>
<td>(Varganahik, 1975)</td>
</tr>
<tr>
<td><em><em>Thermal Conductivity (k</em>) W/m/K</em>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>-0.87×10$^{-6}$×1.85×10$^{-1}$T$^2$+0.78×10$^{-9}$T$^3$</td>
<td>(Polic et al., 2001)</td>
</tr>
<tr>
<td>Vapor</td>
<td>1.31×10$^{-4}$×1.5×10$^{-1}$T$^2$+3.89×10$^{-10}$T$^3$</td>
<td>(Polic et al., 2001)</td>
</tr>
<tr>
<td>Air</td>
<td>-0.0023+1.15×10$^{-4}$T-7.9×10$^{-11}$T$^2$+4.1×10$^{-10}$T$^3$</td>
<td>(Varganahik, 1975)</td>
</tr>
<tr>
<td>Oil</td>
<td>1.06×10$^{-1}$×10$^{-9}$T+3.85×10$^{-12}$T$^2$</td>
<td>(Varganahik, 1975)</td>
</tr>
<tr>
<td>Solid</td>
<td>0.21</td>
<td>(Halter, A. Dhill, &amp; A.K. Datta, 2007a)</td>
</tr>
<tr>
<td><em><em>Permeability (K</em>) m$^2$</em>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td>1.01×10$^{-10}$</td>
<td>(Polic et al., 2001)</td>
</tr>
<tr>
<td>Vapor</td>
<td>1.01×10$^{-10}$</td>
<td>(Polic et al., 2001)</td>
</tr>
<tr>
<td>Diffusivity ($D$) m$^2$/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>0.1436×10$^{-11}$×(1.0+0.167×10$^{-11}$T)</td>
<td>(Hassani, Azouz, Pecalski, &amp; Belghith, 2007)</td>
</tr>
<tr>
<td>Oil</td>
<td>0.1436×10$^{-11}$×(1.0+0.167×10$^{-11}$T)</td>
<td>(Hassani, Azouz, Pecalski, &amp; Belghith, 2007)</td>
</tr>
<tr>
<td><strong>Elasticity (E) Pa</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Of potato discs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Elasticity ($E_{avg}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Gas Constants ($R_M$) J/kg/K</td>
<td>6359</td>
<td>(Poling et al., 2001)</td>
</tr>
<tr>
<td>Air</td>
<td>461.89</td>
<td>(Poling et al., 2001)</td>
</tr>
<tr>
<td>Mixture Viscosity ($N$) Pa</td>
<td>287.05</td>
<td>(Achanta, 1995)</td>
</tr>
<tr>
<td>Latent Heat of Vaporization ($H$) J/kg</td>
<td>2.26×10$^4$</td>
<td>(Poling et al., 2001)</td>
</tr>
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</table>
# Table 4.3, Material Coefficients and Supporting Relations

<table>
<thead>
<tr>
<th>Relation</th>
<th>Eq.</th>
<th>Expression</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusivity ($D^\alpha$)</td>
<td>(2.4), (2.5), (2.6)</td>
<td>$\frac{K^\alpha E}{\mu^\alpha}$</td>
<td>(Achanta, 1995)</td>
</tr>
<tr>
<td>Capillary pressure ($p_c^w$)</td>
<td>(2.4)</td>
<td>$p_c^w = p_g - p^w(\text{Pa}), p_c^w = (0.128005 - 0.185 \times 10^{-3} (T - 273.15)) \times \frac{5627.48}{(S_w + 0.1e - 3) - (1.02 - S_w) + 481952.315 - 203728 \times S_w}$</td>
<td>(Kang &amp; Chung, 2009)</td>
</tr>
<tr>
<td>Capillary pressure ($p_c^e$)</td>
<td>(2.5)</td>
<td>$p_c^e = p_g - p_e(\text{Pa}), p_c^e = \frac{2V}{R_{pore}} \cos \theta (\text{Pa}), R_{pore} = 9 \times 10^{-6} , \text{m}, \theta = 38^\circ, \gamma = 0.024 , \text{N/m}$</td>
<td>(E.J. Pinthus &amp; Saguy, 1994)</td>
</tr>
<tr>
<td>Heat balance relationship</td>
<td>(2.9)</td>
<td>$\rho C_p = \sum_{\alpha=s,w,o,g} \varepsilon^\alpha \rho^\alpha C^\alpha_P, k = \sum_{\alpha=s,w,o,g} \varepsilon^\alpha k^\alpha$</td>
<td>(Oikonomopoulou, Krokida, &amp; Karathanos, 2011)</td>
</tr>
<tr>
<td>Water vapor pressure ($p_{eq}^w$)</td>
<td>(2.10)</td>
<td>$p_{eq}^w = p_{sat}^w(\text{Pa}), p_{sat} = \exp\left(\frac{-6097.9385}{T} + 21.2409642 - 0.0271197T + 0.00001673952T^2 + 2.433502 \log(T)\right) (\text{Pa})$</td>
<td>(Perry &amp; Green, 2008)</td>
</tr>
<tr>
<td>Jacobian ($j^\alpha$)</td>
<td>(2.9)</td>
<td>$0.2354\left(\frac{\rho^e e^e}{\rho^e(1-\phi)}\right) + 0.2292$</td>
<td>(Farinu &amp; Baik, 2007)</td>
</tr>
<tr>
<td>Heat Transfer Coefficient ($h$)</td>
<td>(2.12)</td>
<td>$hA(T_v - T_s) = MC_P \frac{dT}{dt} + \lambda \frac{dW}{dt}$</td>
<td>Experimental</td>
</tr>
<tr>
<td>Mass Transfer Coefficient Water ($h_{mw}$)</td>
<td>(2.13)</td>
<td>$h_{max} = 3617, 4517 \text{ and } 7307 , \text{W/m}^2\text{C at } 150, 170, 190 ^\circ \text{C}$</td>
<td>(Halder et al., 2007b)</td>
</tr>
<tr>
<td>Oil ($h_{mo}$)</td>
<td>(2.14)</td>
<td>$0.01 - 0.2 , \text{m/s}$</td>
<td>(Takhar, 2014)</td>
</tr>
<tr>
<td>Vapor ($h_{mv}$)</td>
<td></td>
<td>$0.25 \times 10^6 - 0.8 \times 10^6 , \text{m/s}$</td>
<td>(Takhar, 2014)</td>
</tr>
</tbody>
</table>

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Fig. 4.1 Surface plots for moisture content of potato disc showing regions modeled
Fig. 4.2 Teflon sample holder with potato disc and thermocouples inserted
Fig. 4.3 Spatial distribution of Temperature inside a potato disc during frying at 170 °C
Fig. 4.4 Experimental and Predicted temperature profiles at surface, 2.5 mm from surface and center of potato disc during frying at 150 °C. AAD between experiment and predicted values was measured to be 12, 10 and 11.6 % for surface, 2.5 mm and center respectively. Error bars indicate ± one standard error, number of replications per time point = 6.
Fig. 4.5 Experimental and Predicted temperature profiles at surface, 2.5 mm from surface and center of potato disc during frying at 170 °C. AAD between experiment and predicted values was measured to be 10.2, 13.3 and 12.5 % for surface, 2.5 mm and center respectively. Error bars indicate ± one standard error, number of replications per time point = 6.
Fig. 4.6 Experimental and Predicted temperature profiles at surface, 2.5 mm from surface and center of potato disc during frying at 190 °C. AAD between experiment and predicted values was measured to be 14.4, 20.8 and 20.2 % for surface, 2.5 mm and center respectively. Error bars indicate ± one standard error, number of replications per time point = 6.
Fig. 4.7 Spatial distribution of moisture inside a potato disc during frying at 170 °C
Fig. 4.8 Spatial distribution of Evaporation rate inside a potato disc during frying at 170 °C
Fig. 4.9 Experiment and Predicted moisture profiles at 150, 170 and 190 °C. AAD of 3.89, 5.7 and 5.5 % was observed at 150, 170 and 190 °C between experiment and predicted values. Error bars indicate ± one standard error, number of replications per time point = 3
Fig. 4.10 Spatial distribution of oil inside a potato disc during frying at 170 °C
Fig. 4.11 Experiment and Predicted moisture profiles at 150, 170 and 190 °C without surface oil removal. AAD of 88, 119 and 90% was observed at 150, 170 and 190 °C respectively. Error bars indicate ± one standard error, number of replications per time point = 3
Fig. 4.12 Experiment and Predicted moisture profiles at 150, 170 and 190 °C with surface oil removed. AAD of 14, 31 and 20% was observed at 150, 170 and 190 °C respectively. Error bars indicate ± one standard error, number of replications per time point = 3
Fig. 4.13 Spatial distribution of Pore Pressure inside a potato disc during frying at 170 °C
Fig. 4.14 Spatial distribution of Gas Pressure inside a potato disc during frying at 170 °C
Fig. 4.15 Spatial distribution of Capillary Pressure inside a potato disc during frying at 170 °C
Fig. 4.16 Spatial distribution of Water Pressure inside a potato disc during frying at 170 °C


