Review Article

Thermal analysis of pre-boiling regime in frying experiments at several sample orientations and gravity levels

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Abstract

The focus of this work is on the extraction of heat transfer coefficients from experimental data during the pre-boiling regime of potato frying by employing a specially designed device. Knowledge of these coefficients is necessary for the estimation of temperature spatial profiles at the inception of frying. In this way, not only understanding but also modeling of the frying process is facilitated. Heat transfer coefficients are estimated based on a one dimensional heat conduction model through matching theoretically predicted with experimentally measured temperature evolutions at three distinct distances below, but close to, the surface of the fried item. The tests cover a variety of experimental conditions regarding the initial oil temperature, fryer geometry, frying surface orientation, type of fried item, and level of gravitational acceleration. The dependence of heat transfer coefficients on the above experimental conditions is discussed.

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1. Introduction

Potato frying involves extraordinarily complex phenomena such as unsteady heat and mass transfer in porous media, phase change of water, vapor bubble formation and growth (boiling) on the food surface and natural heat convection in the oil bulk combined with forced heat convection induced by the violent bubble departure from the food surface (Bouchon and Pyle, 2005; Sahin et al., 1999). However, the early regime of frying (pre-boiling regime) includes only preheating of the potato flesh up to the boiling temperature of water by heat transfer from the oil bulk (van Koerten et al., 2017; Baik and Mittal, 2002; Ni and Datta, 1999). Despite the fact that the pre-boiling regime did not attract enough interest from researchers, understanding this regime is of decisive importance for the entire frying process since it determines the initial conditions for the more complex boiling regime that follows.

Aim of the present work is to estimate the heat transfer coefficients from the hot oil to the frying surface during the pre-boiling regime of frying. The above is necessary to determine the initial conditions for the more complex boiling regime that follows. Estimation of heat transfer coefficients is done by using a one-dimensional heat conduction model whereas experimental temperature profiles (both in the hot oil and inside the fried items) are obtained from frying tests at a variety of experimental conditions. The specific conditions that are expected to significantly affect heat transfer rates during frying are:

- Different fryer geometry: in order to check whether the fryer geometry affects the heat transfer rates, experiments have been conducted in fryers having two different geometries (i.e. cylindrical and rectangular fryer).
- Initial oil temperatures; it is well known that the quality of the fried product (e.g. texture and fat content) depends significantly on the initial oil temperature (Kita and Lisinska, 2005).
- Different types of fried items; besides the frying experiments conducted with a natural porous material (i.e. potato), frying experiments are also conducted with an artificial porous material (frying simulant) to validate the model. Frying simulators (e.g. porous materials saturated with water or glass micromodels), have been used in the past to study a simplified frying process (Lioubbas and Karapantziou, 2015). During the boiling regime of frying, the use of non-deformable artificial porous materials excludes the extra complication induced by the continuous changes of the material characteristics (i.e. material shrinkage, pores development and collapse). Although in the pre-boiling regime of frying we do not expect such changes to occur, it is important to use the same simulant material in the pre-boiling regime, too, to assure continuity with the subsequent boiling regime (that will be dealt with in a subsequent publication). In addition, the different thermal and physical properties of the simulant (e.g. thermal conductivity, capacity, density) offer an additional domain for model assessment.
- Potato orientation (i.e. horizontal facing up, vertical and horizontal facing down); Lioubbas and Karapantziou (2012) have shown that temperature gradients under the potato surface are significantly affected by potato orientation.
- Gravity acceleration levels; Lioubbas and Karapantziou (2015) have shown that higher gravity levels enhance the weak convection currents inside the fryer and drastically boost heat transfer rates.

Modeling of potato frying is a very demanding effort. Direct modeling based on a realistic pore morphology is out of the question. Even pore level modeling attempts are based on artificial geometrical constructions resembling the actual pore structure (Vauvre et al., 2015; Moreira et al., 1995). The conventional approach is based on the homogenization procedure introducing a large number of effective parameters (Lioubbas and Karapantziou et al., 2012; Purlis and Salvadori, 2010). The assessment of such a model against experiments performed under complex external heat transfer conditions is a difficult task since it requires estimation not only of frying parameters but also of parameters influenced by the external to the sample environment (e.g. oil bath). In case of a preheated sample (initial sample temperature close to the boiling one) the initial temperature profile in the potato at the inception of frying is known (e.g. Farid and Chen, 1998). However, this is not the case for in-process potato preheating where the temperature profile is developed by conduction heat transfer to the potato. The idea here is to decouple the pre-boiling conduction-dominated problem (dictated only by the external to the potato conditions) from the complex multi-parameter boiling (i.e., core frying) problem. This analysis leads to a temperature profile that can be used as initial condition for the subsequent boiling regime in a frying model. An inverse heat transfer problem (Ozsik and Orlande, 2003) is set for this purpose. The whole approach here is a typical example of the modern terminology of grey box modeling approach which is based on an appropriate combination of experimental data and theoretical analysis (Cameron and Hangos, 2001).

The structure of the present work is the following: At first, the devices, materials and experimental procedures are described. Then the development of the conduction model, the corresponding numerical solution technique and the justification of the 1-dimensionality assumption are described in detail. Finally, the estimated heat transfer coefficients are presented and discussed extensively.

2. Experimental setup and procedures

2.1. Frying equipment and experimental parameters

Experiments have been conducted in a special designed apparatus that permits testing of various parameters during the pre-boiling regime of frying such as fryer geometry, type of frying item, different exposed surface orientations and increased gravity levels (Fig. 1A). Moreover, our apparatus is capable to elongate the duration of pre-boiling regime of frying by reducing heat transfer from the insulated sides of the porous material.

In order to examine whether the fryer geometry affects the heat transfer rates, experiments have been conducted at two different geometries (i.e. cylindrical and rectangular fryer). In both configurations the same amount (0.5 l) and type of oil (extra virgin olive oil, density and viscosity at 20°C 0.895 g/cm³ and 83 Pa.s, respectively) is used. The heating source is a hot plate (625 W) (Fig. 1A) and experiments are conducted at 4 different initial oil temperatures, T_initial (150, 160, 170, and 180°C) as recommended for commercial deep-fat frying (Gertz and Matthaus, 2006). All experiments are repeated 5 times to check for reproducibility.

Two types of porous samples have been used as fried items; a natural porous material (i.e. potato Agria variety; with dimensions 9.8 x 9.8 x 20.0 mm³, average moisture content 80% w.b) and a frying simulant porous material (Robu, VitrapOR® cylindrical glass filter, diameter: 10.0 mm, height: 10 mm, pore size 10–16 μm, porosity of 42%, inner surface area of 0.50 m²/g) (Srikatidien and Roberts, 2008) fully saturated with water (by means of pressurized air, 2.5 bar). The bottom of the simulant is fixed within a curved glass tube which is filled with water and is used to saturate the porous matrix during experiments. A description of the physical and thermal properties of the porous materials used is presented in Table 1. Values from literature (Sahin et al., 1999) have been used concerning the thermal properties of potato. Since our intention is to model the problem as a one-dimensional approximation, we apply long enough width and depth dimensions (that is, approximately semi infinite domains) that allow excluding complexities induced by the porous sample side surfaces, edges, and corners. For this reason, the porous samples are placed inside a double Teflon trough (one within another) in such a way that their only surface exposed to the oil is flush
with the top of the trough (Fig. 1B). Exposed porous samples surfaces are located 1 cm below the oil–air interface. The side surfaces of the porous samples are prevented from contacting the oil by fixing the potato tightly inside the Teflon troughs. Three different double Teflon trough units are built to accommodate the natural porous samples (i.e. single potato sticks) at different exposed surface orientations (i.e. angles: \( \theta = 0^\circ \); exposed horizontal surface facing up, \( \theta = 90^\circ \); exposed vertical side surface, and \( \theta = 180^\circ \); exposed horizontal surface facing down) (Fig. 1A). By jamming the non-exposed sides of the potato inside the trough units, shrinkage has become marginal. One Teflon trough unit at a time is submerged inside the oil (heating medium).

In order to acquire temperature measurements at positions 0.5, 1.0, and 1.5 mm below the exposed porous surface (Fig. 1B), 3 miniature hypodermic probe thermocouples, with a tip diameter of 0.2 mm, (HYPO-OMEGA) are used. These thermocouples are particularly robust for their small size and have a fast response time (time constant: 0.05 s). A hollow metallic arm holds the thermocouples stably in distinct positions (±0.03 mm) under—but very close to—the porous surface. The thermocouple wires after exiting the hollow metallic arm are connected to a data acquisition unit (Data Acquisition Modules—ADAM, 4018, sampling rate 1 Hz). The bulk oil temperature, \( T_{oil} \), is monitored by 1 T-type (OMEGA) thermocouple (Ø 1.0 mm) placed 1 cm below the oil–air interface and close to the porous surface (1 cm lateral along the y axis).

### 2.2. Hypergravity levels

In order to conduct experiments at the increased gravity levels offered by the large diameter centrifuge (LDC, at ESA/ESTEC) the experimental apparatus presented by Lioumbas and Karapantsios (2012) has been modified (Fig. 1A). In the LDC, the apparatus is housed in freely swinging gondolas which tilt more the higher the rotation speed gets in order to cancel tangential acceleration components and leave only normal acceleration components acting on the spinning specimens. Experiments are performed at gravitational accelerations: 1.0gEarth, 1.8gEarth, 3.0gEarth, 6.0gEarth, and 9.0gEarth. As soon as the desired gravity level is achieved at the LDC (after about 1 min of spinning), the head of an electro-hydraulic jack is commanded to lift the hot plate and the fryer until the free surface of the hot oil reaches 1 cm above the porous surface. Tests at increased gravitational acceleration levels have been conducted only with oil at 150°C.

### 3. Mathematical problem formulation

The problem is assumed to be one-dimensional locally at the sample (potato or simulant) domain showing temperature variation only in the direction perpendicular to the sample. This assumption is confirmed by appropriate computations latter in this section. Whereas the heat transfer mechanism inside the sample is well understood (conduction), the same is not true for the oil side. There is definitely convection due

---

**Table 1 – Description of the physical and thermal properties of the used materials at 25°C.**

<table>
<thead>
<tr>
<th>Property</th>
<th>Dry potato</th>
<th>Water</th>
<th>Bulk</th>
<th>Glass</th>
<th>Water</th>
<th>Bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, kg/m³</td>
<td>1480</td>
<td>1020</td>
<td>1089</td>
<td>2230</td>
<td>1020</td>
<td>1720</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.263</td>
<td></td>
<td></td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture, w/w, (wet basis)</td>
<td>0.80</td>
<td></td>
<td></td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture, v/v, (wet basis)</td>
<td>0.85</td>
<td></td>
<td></td>
<td>0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture, w/w, (dry basis)</td>
<td>4.00</td>
<td></td>
<td></td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture, v/v, (dry basis)</td>
<td>5.80</td>
<td></td>
<td></td>
<td>0.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity, W/mK</td>
<td>0.54</td>
<td>0.60</td>
<td>0.59</td>
<td>1.13</td>
<td>0.60</td>
<td>0.99</td>
</tr>
<tr>
<td>Heat capacity, J/(K°*kg)</td>
<td>3200</td>
<td>4179</td>
<td>4000</td>
<td>800</td>
<td>4179</td>
<td>1650</td>
</tr>
<tr>
<td>Thermal diffusivity, m²/s°10⁰</td>
<td>1.14</td>
<td>1.41</td>
<td>1.35</td>
<td>6.33</td>
<td>1.41</td>
<td>3.49</td>
</tr>
</tbody>
</table>
to oil motion but this motion is undetermined. So, a detailed model of heat transfer in the oil is not possible and the uncertainty is transferred from the unknown velocity profile in the oil to an unknown oil-to-sample heat transfer coefficient. The direct heat transfer mathematical problem for temperature evolution in the sample is the following (Ozisik, 1989):

\[
p \rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} k(T) \frac{\partial T}{\partial z}
\]

(1)

where \( t \) is the time, \( z \) is the direction towards sample interior \((z = 0 \text{ at oil-sample interface}), T \) is the local temperature in the sample, \( \rho \) is the sample density, \( c_p \) is the sample specific heat capacity and \( k \) is the sample conductivity

Eq. (1) goes together with the following boundary conditions:

(1) Heat can in principal reach the inner edge of the sample \((z = L)\) in two ways: (i) through the sample itself and (ii) through the bottom of the Teflon double trough unit which is also exposed to oil. The thermal conductivity of Teflon is smaller than the thermal conductivity of the sample and moreover its thickness is larger than the sample thickness so the situation can be described by requiring no heat flux at the particular location:

\[
\frac{\partial T}{\partial z} = 0 \text{ at } z = L
\]

(2)

The approximate nature of this condition has no practical influence on the measured quantities (recordings of the three thermocouples below the exposed surface of the sample) since it is set too far from the measurement points, and because heat has slightly penetrated the sample during the short pre-boiling period.

(2) The boundary condition at the sample-oil interface has the form:

\[
k(T) \frac{\partial T}{\partial z} = h(T - T_{\text{oil}})
\]

(3)

It is noted that both the heat transfer coefficient \( h \) and the oil temperature \( T_{\text{oil}} \) are in general time depended.

The initial condition for the above problem is that \( T = T_0 \) everywhere in the sample at \( t = 0 \) \((T_0 \text{ is the initial sample temperature})\).

The mathematical model quantities must be related to the actual measured quantities. The \( T_{\text{oil}} \) in Eq. (3) refers to the oil temperature above the sample. It is assumed that the oil experiences a high degree of mixing and so its temperature is everywhere alike. So, \( T_{\text{oil}} \) in Eq. (3) is the experimentally measured oil temperature. The temperature readings of the three thermocouples represent the area average temperature at the region of contact between sample and thermocouple so

\[
T_{\text{mi}} = \frac{1}{A_i} \int_{A_i} T_{\text{dA}}
\]

(4)

where \( T_{\text{mi}} \) and \( A_i \) are the temperature reading and the area of thermocouple 1, respectively.

The next step is the computation of the physical properties of the sample. It is a composite material so its physical properties are appropriate averages of its constituent properties. The product \( \rho c_p \) is a volumetric property (structure independent) and it can be determined for the sample as \( \rho c_p = \varphi (\rho c_p)_w + (1 - \varphi) (\rho c_p)_s \) where the subscripts "w" and "s" refer to properties of water and dry material, respectively, and \( \varphi \) is the volume fraction of water. The product \( \rho c_p \) for water exhibits only a slight temperature variation in the temperature region under consideration so it can be considered as constant. On the other hand, the thermal conductivity is a structural property that depends on spatial distribution of the constituents in the sample. There are two bounds in the thermal conductivity of a random composite material: the lower "in series" bound \( k = (\varphi/k_w + (1 - \varphi)/k_s) \) and the upper "in parallel" bound \( k = \varphi k_w + (1 - \varphi) k_s \) (Adler, 1992). The two bounds approach each other as \( k_s \) approach \( k_w \). Here the "parallel" model is used (the choice is not really essential because \( k_w \) and \( k_s \) are close to each other so both models show similar results). The thermal conductivity of water is taken as a linear function of temperature whereas for potato and simulant can be taken as constant based on literature (Srikiatden and Roberts, 2008) and supplier information, respectively. So overall, \( k \) can be assumed as a linear function of temperature.

The only unknown parameter in the problem is \( h \) which must be found by employing the experimental information for \( T_{\text{mi}} \). Following the classification of inverse problems (Ozisik and Orlande, 2000), the present one is a non-linear, one dimensional, boundary condition, inverse conduction problem. Before discussing the inverse problem, an algorithm for the solution of the direct problem (i.e. computing \( T_{\text{mi}} \) for given \( h \)) is developed. A variety of numerical methods is available for the solution of the transient conduction equation. Apparently, a method is needed having the same structure with the one used in frying simulations (Moreira et al., 1995) in order to build the frying model by adding dominant phenomena. So, the choice is second order finite differences for spatial discretization and explicit Euler method for time discretization. The position of the thermocouples sets the requirement for fine resolution \((\text{e.g.} 50 \text{ points/mm})\), and given the length of the domain, a very large number of discretization points are needed. This was not the case in a previous work (Lioumbas et al., 2012) where the measuring thermocouple was located at the edge of the computational domain (potato center). The idea here is to invoke the slight nonlinearity of the governing equation, to truncate the domain at \( z = L_c \), to solve analytically the linear equation for \( z > L_c \) and to use the analytical solution to develop a boundary condition at \( z = L_c \).

The following non-dimensionalization is introduced \((\text{where } k = k_w + k_1(T - T_0) \text{ and } T_0 \) is the boiling temperature of water used as reference temperature):

\[
\hat{T} = \frac{T - T_0}{T_S - T_0}, \quad \tau = \frac{k_1 t}{\rho c_p L_c^2}, \quad \hat{T}_{\text{col}} = \frac{T_{\text{col}} - T_0}{T_S - T_0},
\]

\[
\hat{h}(t) = h(t)/h_0, \quad \epsilon = \frac{k_1(T_S - T_0)}{k_0}, \quad \hat{z} = z/L_c
\]

The governing equations take the form

\[
\frac{\partial \hat{T}}{\partial \tau} = \frac{\partial}{\partial \hat{z}} (1 + \epsilon \hat{T}) \frac{\partial \hat{T}}{\partial \hat{z}} = 0 \leq \hat{z} \leq 1
\]

(5)

\[-(1 + \epsilon \hat{T}) \frac{\partial \hat{T}}{\partial \hat{z}} = \hat{h}(\hat{T}_{\text{col}} - \hat{T}) \quad \hat{z} = 0
\]

(6)

\[
\hat{T} = \int_{y=0}^{1} \frac{1}{(r - y)^{1/2}} \frac{\partial \hat{T}}{\partial y} \, dy \quad \hat{z} = 1
\]

(7)

The last boundary condition is derived by setting \((\text{as an approximation far from the measuring locations}) \epsilon = 0 \text{ for } z > L_c\).
and solving analytically the resulting linear transient conduction equation for an arbitrary heat flux at the boundary \( z = L_c \). The boundary condition (7) is of memory type, connecting the instantaneous boundary temperature to its history from the start of heating. The above system of equations is discretized using central second order differences in the domain and one side second order differences at the boundary (Pozrikidis, 1998) The singularity in the integrand of the boundary condition has been removed by employing stagewise analytical integration. The discretized equations are (where \( N \) is the number of spatial discretization steps):

\[
\begin{align*}
\bar{T}_i^{(j+1)} & = \bar{T}_i^{(j)} + \frac{\delta T}{(62)} \left\{ (1 + \varepsilon) \frac{\bar{N}^{(j)} + \bar{N}^{(j+1)}}{2} (\bar{T}_i^{(j)} - \bar{T}_i^{(j+1)}) \\
& - (1 + \varepsilon) \frac{\bar{N}^{(j-1)} + \bar{N}^{(j)}}{2} (\bar{T}_i^{(j)} - \bar{T}_i^{(j-1)}) \right\} \text{ for } i = 1 \text{ to } N
\end{align*}
\]

(8)

\[
\begin{align*}
\bar{T}_N^{(j+1)} & = \frac{B_N \bar{T}_{Teflon} + 4 \bar{N}_T^{(j+1)} - \bar{N}_T^{(j)}}{2 \delta z} \left\{ \frac{3}{2 \delta z} + \frac{B_N}{1 + \varepsilon \bar{T}_N^{(j+1)}} \right\}^{-1}
\end{align*}
\]

(9)

\[
\begin{align*}
\bar{T}_0^{(j+1)} & = 2 B_0 \left( \frac{1}{\pi} \sum_{k=1}^{\infty} \frac{1}{2} \frac{\bar{T}_2^{(j-k)}}{4 \bar{T}_1^{(j-k)}} + 3 \bar{T}_1^{(j-k)} \right) \\
& \left\{ \bar{k} - k + \frac{1}{2} \right\} \left\{ \bar{k} - k + \frac{1}{2} \right\}
\end{align*}
\]

(10)

where \( \bar{T}_0^{(j)} \) is the value of dimensionless temperature at the location \( z = 1 - \delta z \) and at time \( t = \bar{t} \delta \bar{t} \) whereas \( \delta z, \delta \bar{t} \) are the spatial and temporal discretization steps, respectively.

The required readings of thermocouples can be computed by taking the average temperature of all points being in contact with each thermocouple. Let us say the center of a thermocouple coincides with the discretization point having \( i = i \). The discretization step is such that \( J \) steps coincide with the thermocouple radius. The thermocouple temperature evolution is computed as:

\[
\dot{T}_m = \frac{1}{w_0 + \sum_{i=1}^{j-1} (\bar{T}_{1,i} + \bar{T}_{1,i+1}) w_i}
\]

(11)

where \( w_i \) (\( i = 0 \) to \( j - 1 \)) are the weighting coefficients mapping the one-dimensional temperature profile to the two-dimensional circular area of the thermocouple (\( w_i = f_1 \)).

The above approach permits a very efficient direct problem solution for an arbitrary \( h(t) \) function. Typically, the inverse problem solution procedure requires expansion of the unknown function to a set of basis functions and seeking for an expansion coefficient under certain deviation minimization requirements (Alifanov, 1994). Unlike the usual case in which the effort is to test inversion algorithms using artificial data (Brociek et al., 2014), effort here is to really estimate the unknown coefficient \( h \) from experimental data. Since the data are real and not manufactured they are imposed to experimental accuracy restrictions. Nevertheless, the total amount of required work is limited (only a finite set of data has to be analyzed) so it is found convenient to do the inversion procedure by inspection in order to have direct control of the fitting procedure instead of invoking strict mathematical requirements and making the procedure automatic. For example, the decision for the time period for which fitting is pursued is rather subjective and it is difficult to become part of an automated inverse problem algorithm. The expansion to basis function is of a novel type and is ideally suited to the manual seeking for best results. A number \( N \) of basis function is assumed. Then \( N \) pairs of \( h_i \) and \( t_i \) are considered (\( i = 1, 2, \ldots, N \)). The corresponding \( h(t) \) function is the one that interpolates linearly the pairs \( h_i, t_i \). The procedure starts from \( N = 1 \) and continues by increasing \( N \) until a fair approximation of the measured thermocouple temperature is achieved.

A discussion on the validity of the one dimensional approximation is made here. Two-dimensionality might arise from three possible origins: (i) variation of \( h \) along the exposed surface of the sample. The sample surface is a small portion of the Teflon specimen (double trough unit) surface so it can be assumed that \( h \) is uniform at the sample level. Apparently, this is an assumption compatible with the use of \( h \) instead of a detailed temperature field in the oil. (ii) Heat exchange with the Teflon specimen. The thermal diffusivity of the potato sample is very close to that of Teflon so there is no significant temperature difference at the potato-Teflon interface to promote heat exchange. In the case of simulant, heat exchange is suppressed not from the temperature difference at the simulant-Teflon interface (which exists since thermal diffusivity of the simulant is higher from that of Teflon) but from the thermal conductivity difference between simulant and Teflon. (iii) Heat penetration from the lateral surface of the Teflon specimen. The distance of the three temperature measuring points from the closest lateral surface is at least ten times larger than the distance from the sample surface exposed to oil. All the above arguments strongly support the assumption of a 1-dimensional profile.

Yet, in order to verify the assumption several two-dimensional computations are performed. Typical two dimensional geometries (planar for potato and axisymmetric for simulant) are considered. The extreme condition of \( h \) equal to infinity (worst case scenario regarding lateral temperature uniformity) is examined. The physical properties of potato and simulant sample and Teflon are introduced in the model and the transient heat conduction equation is solved in both domains (sample and Teflon) using a finite element code and assuming oil is in contact with both the top and side specimen surface. The simulations showed that there is no measurable effect of the lateral dimension on the temperature evolution at the location of the thermocouples until the third thermocouple (that at largest distance, 1.5 mm, from the exposed surface) reaches 90 °C. The latter is certainly a temperature close to the end of the pre-boiling regime (beyond the time period of the fitted data). A typical temperature contour plot for the potato sample at a specific time instant is shown in Fig. 2. This time instant corresponds to the moment that the third thermocouple reaches 80 °C. One can easily see the one dimensional character of the temperature profile in the sample especially at the location of the thermocouples (middle of the sample width; designated as plane of symmetry in the plot). It is noted that for larger times the side heat front will eventually approach the sample-Teflon interface and the profile will lose its one-dimensionality progressively from the bottom to the surface of the sample.
4. Results and discussion

4.1. Experimental parameters applied to model

The model is adjusted to fit the measured temperature evolution curves aiming to identify the simplest form of \( h(t) \) that approximates reasonably the data. The simulation stops before the onset of bubbling on the sample surface which not only changes dramatically the heat transfer coefficient but also renders the conduction model inappropriate to predict heat transfer in the sample. The onset of bubbling is recognized either by the sudden noticeable temperature rise inside the porous materials or/and by observing the generated bubbles. It is stressed that in reality bubbling at the exposed surface starts usually before the surface temperature reaches the water boiling point. This is compatible with the concepts of (i) existence of surface water (breaking of the effective homogeneous medium theory on the sample-oil interface) (Cameron and Hangos, 2001; Chevasathianchaiporn and Tangduangdee, 2009) and (ii) water degassing (bubbles created by desorption of dissolved air) prior to boiling (Lioumbas et al., 2012). Computations also show that the temperature profiles are close to linear at the scale of the thermocouple contact area so the average temperature computed by Eq. (11) is the same with the temperature at the center of the thermocouple contact with a small deviation only for the first thermocouple and for small times. A sensitivity analysis shows that both the choice of \( L \) for natural boundary condition (2) and \( L_c \) for artificial boundary condition (7) does not influence the fitting results. The above procedure produces good results for the case of a potato sample. The evolution of temperatures measured by the three thermocouples and the corresponding model predictions for the potato sample for several experimental conditions including different initial oil temperature, different fryer geometry, gravity level and different exposed surface orientation are coming next.

4.2. Influence of \( T_{\text{oil}} \) on pre-boiling regime

Fig. 3 shows that boiling initiates faster as \( T_{\text{oil}} \) increases. In any case the model predictions are in very good agreement with experimental measurements. It appears that there is no systematic dependence of \( h(t) \) from the \( T_{\text{oil}} \) since the corresponding estimated profiles (not shown) are similar. This is because the measured drop of the oil temperature when the specimen is immersed to the oil is independent from the initial oil temperature and this is the reason that the induced convection motion is similar for all initial oil temperatures. Specifically, the oil bath is heated from below to compensate losses to the environment so there are natural convection currents in it even before the specimen immersion. The following physical picture arises as regards the phenomena occurring after the immersion of the specimen in the oil bath. At first, heat is transferred from the oil to the specimen through conduction (thermal shock due to their different temperatures). The reduction of oil temperature due to thermalization of the specimen triggers the temperature controller of the experimental system to start heating the oil intensifying the macroscopic motion of oil in the bath due to natural convection. This oil motion induced by natural convection in the bath appears as forced convection when viewed from the perspective of heat transfer from the oil to the specimen. This is why the above is henceforth termed simply as convection. The direct simulation of the above phenomena not only requires solution of the transient Navier–Stokes and heat transfer equations in a complex three dimensional geometry but it also has to take into account the operation time profile of the heating element controller which is unknown. Such a general model is completely useless with respect to our final purpose to model the frying process and this is why the use of the heat transfer coefficient concept is necessary.
Fig. 3 – Effect of $T_{\text{oil}}$ on the temperature profiles inside the porous material: (a) $T_{\text{oil}} = 150^\circ$C; (b) $T_{\text{oil}} = 160^\circ$C; (c) $T_{\text{oil}} = 170^\circ$C; (d) $T_{\text{oil}} = 180^\circ$C. Experimental conditions: gravitational acceleration = 1.0g$_{\text{earth}}$, porous material = potato, frying surface orientation = horizontal facing up ($\theta = 0^\circ$), oil bath = cylindrical beaker. The light blue and pink stripes denote the period of heating (pre-boiling) and the period of boiling, respectively. The plots present the experimental (gray lines) and predicted (dotted lines) temperature profiles at 3 distances below the potato surface (0.5 mm: dots, 1.0 mm: dashed line, 1.5 mm: dense dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4 – Effect of fryer geometry on the convective heat transfer coefficients and the temperature profiles inside the porous material (right column: rectangular fryer; left column: cylindrical fryer). Frying surface orientation horizontal facing up ($\theta = 0^\circ$); initial oil temperature 150°C. The top plots present the predicted $h$ profiles (left axis) as well as the predicted and measured $T_{\text{oil}}$ profiles (right axis). The bottom plots present the experimental (gray lines) and predicted (dotted lines) temperature profiles at 3 distances below the potato surface (0.5 mm: dots, 1.0 mm: dashed line, 1.5 mm: dense dashed line).
4.3. Influence of fryer geometry on pre-boiling regime

Fig. 4 shows how the fryer geometry affects the pre-boiling regime. Specifically, for the rectangular fryer $T_{oil}$ profiles attain their minimum value (i.e. 140 °C) sooner (45 s) compared to the cylindrical fryer (150 s), but also sooner return back to the $T_{oil}$ set point (i.e. 150 °C). This indicates better heat transfer rates for the case of the rectangular fryer for both water and sample and between heater and oil. This results to higher temperatures inside the sample, shorter pre-boiling regime and the computed $h(t)$ profiles attain larger values for the rectangular fryer. The higher $h$ value at $t = 0$ sec observed for the cylindrical fryer is attributed to the instantaneous temperature gradient at the moment of the specimen immersion inside the oil bath caused by the different topology. Therefore, the fryer geometry affects significantly the temperature gradients inside the fryer and as a consequence the pre-boiling regime as well. However, the model predictions for the potato sample are in good agreement with the temperatures evolution measured by the three thermocouples in both fryers geometry. In order to exclude the influence of the geometry on the experimental results, the results presented hereafter always correspond to the same fryer geometry.

4.4. Influence of frying surface orientation on pre-boiling regime

Fig. 5 shows how different orientations of the exposed surface affect the temperature profiles inside the sample. The effect of surface orientation on heat transfer coefficient is clearly shown in Fig. 6 (1.0g_{earth}, terrestrial conditions). The well known initial conduction burst is apparent in all surface orientations. Furthermore, in all surface orientations the coefficient $h$ diverges to a convection dominated steady value quickly after the initial burst. For the horizontal facing up case, $h$ attains the lowest value among the three orientations since the exposed surface is not wetted directly by the ascending convection currents in the oil but only indirectly by the global macroscopic motion of the oil in the bath. On the contrary, for the vertical orientation, the final value of $h$ is the highest of all because ascending convection currents are in direct contact with the exposed surface of the sample (considering the specimen geometry). In the case of the horizontal facing down orientation, rising hot oil layers are trapped at the sample surface and once this is done then convection becomes less important leading to lower $h$ values, alike those encountered at the horizontal facing up orientation, dictated by the global motion of oil in the bath.
4.5. Influence of gravitational acceleration on pre-boiling regime

Fig. 7 shows that as gravitational acceleration increases, temperature profiles attain larger values inside the sample and boiling starts sooner. Once again the model succeeds to predict the temperature gradients evolution inside the sample. The effect of gravity level on heat transfer coefficient evolution is presented in Fig. 8 for the horizontal facing up, horizontal facing down and vertical surface orientations, respectively. In the case of the horizontal facing up orientation the variation of $h$ versus time is qualitatively the same for all gravity levels. Nevertheless, the final steady values increase as gravity level increases but not in a linear fashion, Fig. 8a. This is a confirmation of the hypothesis that heat is transferred by forced convection (at the sample level) which is induced by natural convective motion (at the oil bath level). In the case of the horizontal facing down orientation, Fig. 8b, only a moderate effect is found when increasing the gravity level and this only for short times since at long times all values lie in proximity. This is compatible to the notion that at this orientation convection currents are suppressed at the bottom side of the specimen and so the global motion of oil in the bath governs chiefly heat transfer which means that only secondary convective currents and not the main rising currents in the bath affect the exposed surface. Finally, a quite different time profile of $h$ appears in case of the vertical surface orientation (Fig. 8b). Heat transfer coefficient initially increases with time and then decreases with the phenomenon being more intense as gravity level increases. The final $h$ values are considerably larger than for other orientations and increase with gravity. Evidently, heat transfer is dominated by convection currents but the reason for the initial non-monotonic behavior is not clear and it might be attributed to the specific geometric features of the specific setup (since the same behavior is not seen in the different set-up used for terrestrial experiments (see Fig. 6)).

van Koerten et al. (2017) provide an engineering model to describe the heat transfer coefficient during frying due to water evaporation and suggest that heat transfer coefficients over a period of $\sim 30$ s before frying initiation attain values from $\sim 500$ to $350$ W/m$^2$K. van Koerten et al. (2017) attribute the theoretically predicted reduction of the convective heat transfer coefficient to the outer temperature gradient decrease. It must be noted that the above range is quite comparable with the values proposed in the present study (e.g. a range $150$–$300$ W/m$^2$K for the vertical surface orientation). It must be stressed, however, that comparison with natural convection heat transfer coefficients from literature is somewhat misleading. These coefficients refer to the surface (object) that initiates natural convection. In the present study (as discussed in the manuscript), natural convection is induced from the hot bottom surface of the fryer (oil bath) which is different from the frying surface (potato or simulant) where the heat transfer coefficient is evaluated.

4.6. Influence of the type of porous material on pre-boiling regime

Fig. 9 compares the temperature profiles inside the natural (potato) and the artificial (simulant) porous materials for the same $T_{col}$ (i.e. $150$ °C), oil bath geometry (rectangular) and exposed surface orientation (horizontal facing up) but at two different gravitational acceleration values (i.e. 3.0 and
Fig. 8 – Dependence of the convection heat transfer coefficient, $h$, on various gravitational levels for all examined surface orientations: (a) horizontal facing up ($\theta = 0^\circ$), (b) horizontal facing down ($\theta = 180^\circ$); (c) vertical ($\theta = 90^\circ$). (Experimental conditions: $T_{oil} = 150^\circ$C; porous material = potato, oil bath = rectangular).

As a result, heat penetrates faster in glass than in water. The readings of each thermocouple depend on the fraction of its contact area with water which is of course an undetermined quantity. The real useful outcome here is that there is no reason to try modeling the frying process using a homogeneous conduction model. A two component conduction model is needed but still the contact fraction of each thermocouple to each component is an unknown quantity and the only way to determine it is by fitting the model predictions to the temperature data from the pre-boiling period.

5. Conclusions

A conduction model has been employed to estimate the oil-to-sample heat transfer coefficients during the pre-boiling regime of frying under different experimental conditions. Among those conditions, special attention is paid to the role of the frying surface orientation and of the level of gravitational acceleration as these conditions are scarcely examined in literature despite their potential for industrial innovation. The inability to solve the oil bath heat transfer problem has led to the set up of an inverse heat transfer problem for the determination of an oil-to-sample heat transfer coefficient based on
intra-sample temperature measurements. In case of a potato sample, the solution of the inverse problem allowed estimation of the heat transfer coefficient and of the intra-sample temperature profile that can be used as initial condition in the subsequent boiling regime in frying simulations. The relation of estimated heat transfer coefficients to the experimental conditions is discussed. In the case of a frying simulant material the experimental data are incompatible to the employed homogeneous conduction model suggesting that the assumption of thermal equilibrium between phases must be relaxed.

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References

Gertz, C., Matthaus, B., 2006. Optimum Deep-Frying, Recommendations by the German Society for Fat Science. DGF.


