Effect of Potato Orientation on Evaporation Front Propagation and Crust Thickness Evolution during Deep-Fat Frying

John S. Lioumbas and Thodoris D. Karapantsios

Abstract: The various theoretical approaches that have been proposed for modeling heat and mass transport during deep-fat frying of potatoes do not take into account the effect of potato orientation with respect to gravity. This can be partly attributed to lack of systematic experimental information at different orientations. The objective of the present work is to experimentally study the effect of potato orientation on the evaporation front propagation and crust thickness evolution and how this effect varies with frying conditions. To achieve this goal, a special device has been constructed which, among others, permits: (a) exposure of only one surface of a potato stick to hot oil, (b) rotation of this potato surface at 0°, 90°, and 180° with respect to gravity, and (c) accurate placement of miniature thermocouples under—but very close to—the exposed potato surface. Crust thickness is determined by 2 independent methods: (a) microphotography and (b) a micrometer. It is found that the evaporation front propagation and crust thickness evolution are different among the examined surface orientations. The fastest heat penetration and thickest crust are measured at vertical (90°) surfaces. The implications of this finding regarding potato texture and energy consumption are discussed.

Keywords: bubbles, crust thickness, evaporation front, frying, orientation, potato, temperature measurement

Practical Application: Understanding the role of surface orientation on the crust evolution and the propagation of the evaporation front inside the food is of particular value to:

- Deterministic modeling efforts of the coupled heat and mass transfer phenomena during deep-fat frying, and
- food industry; the present data suggest that crispier food is produced and less energy is consumed when the food is placed at a nonhorizontal position inside the fryer.

Introduction

Several researchers in the past have recognized that heat and mass transfer rates inside a food being fried are different among different sides of the food. Sahin and others (1999) measured the temperature profiles at the top and the bottom surface of slices of potatoes (0.05 × 0.05 × 0.005 m), whereas Farinu and Baik (2007) did the same for sweet potato disks (diameter 0.025, 0.035, and 0.040 m; width 0.010 cm), during deep-fat frying. Their results were contradictory, since Sahin and others (1999) reported higher heat transfer rates at the bottom surface of their samples, while Farinu and Baik (2007) observed higher heat transfer rates at the top surface of their samples. Costa and others (1999) based on qualitative visual observations (without presenting any recorded images) suggested that the boiling heat transfer coefficient, h, may be position-dependent, since the agitation of oil by departing bubbles at the top surface of a potato stick can increase h values, while the opposite may happen at the bottom surface due to adhering large vapor bubbles which increase resistance to heat transfer. Southern and others (2000) while performing preliminary tests in order to decide which potato chip orientation suits them best for their main experiments, that is, horizontal or vertical; concluded that the vertical position results in a faster moisture loss rate compared to the horizontal position. Recently, Ziaiifar and others (2009) measured both the bottom and the top crust thermal conductivity of single potato samples (0.05 × 0.05 × 0.006 m) fried at isothermal conditions (170 °C). They found that the top crust conductivity is lower than the bottom crust, which implies structural differences between the top and the bottom crust and they suggested that the lower conductivity corresponds to a drier crust because of the different heat transfer coefficient values.

From the above, it is apparent that although it has been recognized that different heat and mass transfer rates are expected at the various surfaces of a fried food (that is, top, bottom, and side) and several speculations have been made to explain the differences, there is still no satisfactory understanding of the underlying phenomena. As a consequence, all frying modeling efforts so far do not take into account the differences between the various sides of the fried food. This can be partly attributed to lack of systematic experimental information concerning the effect of food orientation on the temperature field inside the developing crust to validate the models. Placing accurately a very thin thermocouple at a well-defined position under the potato surface and keeping it there during frying as crust develops is a challenging task. The unavailability in past years of miniature, yet robust, thermocouples along with extensive potato shrinkage phenomena did not

MS 20120524 Submitted 4/9/2012, Accepted 7/19/2012. *Authors are with Div. of Chemical Technology, Dept. of Chemistry, Aristotle Univ. of Thessaloniki, Box 116, 541 24 Thessaloniki, Greece. Direct inquiries to author Karapantsios (E-mail: karapant@chem.auth.gr).*

doi: 10.1111/j.1750-3841.2012.02915.x

allow researchers to measure accurately local temperatures inside the crust.

Recently, Lioumbas and Karapantsios (2012) constructed a special device in order to examine the relationship between crust thickness evolution and evaporation front propagation during deep-fat frying of single potato sticks having only their top surface exposed to hot oil. These authors combined temperature recordings at different locations inside the developing crust with independent crust thickness measurements. In the present study, this device has been modified in order to permit rotation of the exposed surface to 90° and 180° with respect to the gravity vector. The objective is to provide methodical experimental evidence regarding the influence of potato orientation on the evaporation front propagation and crust thickness evolution during frying. This is deemed extremely important since vertical—or inclined—surfaces constitute a large part of potato sticks during deep-fat frying.

The present study is part of a project, funded by the European Space Agency, for the definition of critical points for the design and optimization of the frying process under altered gravity conditions (microgravity and hypergravity). Apart from preparing home-like fried foods for astronauts (which will play an important psychological role during future long duration space missions), this project offers the unique opportunity to modulate gravity and so examine the physical mechanisms of frying under a new fundamental perspective. It must be stressed here that our interest is on finish frying of raw potatoes since astronauts during space missions cannot carry a cargo of preprocessed potatoes but instead they will grow their own potatoes. In addition, finish frying of raw potatoes can serve as reference for comparisons in subsequent work with preprocessed potatoes.

Materials and Methods

The experimental setup and procedures are similar to those employed by Lioumbas and Karapantsios (2012). Only some basic features are presented here. It must noticed that the all the data presented in this study for $\theta = 0°$ are based on experiments presented by Lioumbas and Karapantsios (2012). A potato stick (Agria variety, average moisture content 80% wb) with dimensions 9.8 × 9.8 × 20.0 mm is placed inside an insulating double TEFLON trough unit. The potato sample is placed inside the inner Teflon trough in such a way that its only surface exposed to the oil is flush with the top of the trough. Three different double Teflon trough units are built to accommodate single potato sticks at different orientations (Figure 1). The trough units allowed putting the potato at angles: $\theta = 0°$ (exposed horizontal top surface), $\theta = 90°$ (exposed vertical side surface), and $\theta = 180°$ (exposed horizontal bottom surface). By jamming the nonexposed sides of the potato inside the trough units, shrinkage has become marginal (see below). One Teflon trough unit at a time is submerged inside the heating medium.

The heating medium is extra virgin olive oil (ELAIS S.A.; density 0.895 g/cm^3 and viscosity 83 cP, at 20 °C). The oil is contained in a cylindrical beaker placed on a hot plate (625 W nominal power). Experiments are conducted at 4 different initial oil temperatures T_{in} (that is, 150, 160, 170, and 180 °C) and are repeated 5 times to check for reproducibility.

The following temperature measurements are simultaneously acquired at 1 Hz (ADAM, 4018):

- T_{oil}: Temperature profiles of bulk oil, which are made slightly nonisothermal in order to simulate conditions usually encountered at catering applications (Lioumbas and others 2012a) (*that is, kg potatoes to oil volume ratio approximately 1/35* $Kg_{potatoes}/L_{oil}$).
- T_s: Temperature profiles from a thermocouple placed at the potato–oil interface. T_s profiles do not correspond to the actual temperature of the potato surface as the thermocouple is partially affected by the bulk oil temperature. Nevertheless, this measurement provides qualitative information for the onset and progress of frying.
- T_p: Temperature profiles below the potato–oil interface and inside the developing crust. Three miniature hypodermic probe thermocouples, with a tip diameter of 0.2 mm, (HYPO-OMEGA), are used to acquire T_p profiles at positions 0.5, 1.0, and 1.5 mm below the exposed potato surface. These thermocouples are placed apart by 3 mm in the lateral direction (parallel with the exposed surface) in order to avoid interference and masking effects that are believed equally important sources of discrepancies with local variability of the potato. Moreover,

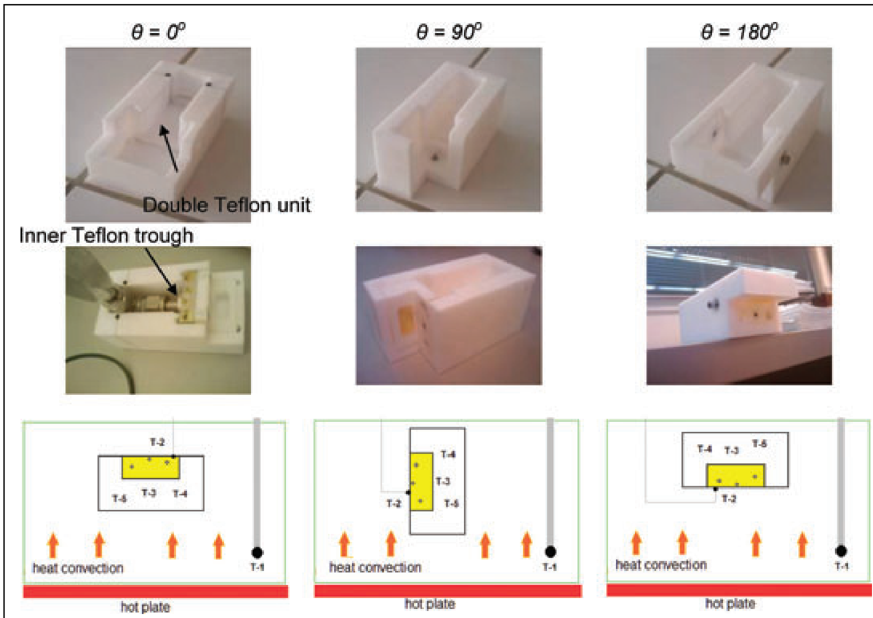

Figure 1–Photographs of the 3 double Teflon trough units and schematic depiction of different potato's exposed surface orientation; T-1, T-2, T-3, T-4, and T-5 designate thermocouples inside the bulk oil, the potato–oil interface, and under the potato surface, respectively.

as these thermocouples are firmly fixed at their positions, they significantly resist shrinkage. Details concerning the accuracy and the reproducibility of the measuring method can be found elsewhere (Lioumbas and Karapantsios 2012).

The thickness of the crust is determined by 2 individual methods (accurate down to ± 0.01 mm): (a) by image analysis of microphotographs and (b) by a digital electronic micrometer (SYLVAC). Details concerning the procedure followed for the crust thickness determination can be found elsewhere (Lioumbas and Karapantsios 2012). Crust is defined (for example, Ziaiifar and others 2010) as the top completely dry layer of a fried potato which exhibits different texture (color, rigidity, and coarseness) and structure (porosity and pore size) from the rest of the potato flesh (core). Potato samples meant for crust thickness measurement were taken out of the fryer at specific instants: 300, 500, 1000, and 1500 s when frying at 150 °C and 100, 200, 400, 700, and 1000 s when frying at 180 °C. Thickness measurements are carried out at 10 different crust sections of 5 different potato samples in order to increase the confidence of the calculated statistics.

Results and Discussion

Bubble behavior on potato surfaces

This section presents a qualitative description of the influence of potato orientation on bubble behavior at the exposed potato surface. This description is based on visual observations and we believe that it will assist interpreting the experimental evidence of subsequent sections. To the best of our knowledge, frying literature does not contain systematic information regarding bubble characteristics (for example, bubble rising velocity, size, trajectory, and so on).

Figure 2 presents schematically the bubble behavior observed on the 3 differently orientated exposed potato surfaces:

- Horizontal top exposed surface ($\theta = 0^{\circ}$): In this case, the exposed surface does not come in direct contact with the vertical natural convection currents rising from the bottom of the container. Only some weak horizontal convective currents, owing to the small oil recirculation inside the container, influence the top surface. As a result, bubbles grow and detach chiefly under the influence of the momentum of the vapor ejected through the potato surface and of buoyancy. In several occasions, bubbles at the surface of the potato merge to larger ones and then detach. The trajectory of rising bubbles is essentially vertical all the way from the potato surface to the oil/air interface indicating limited interaction between neighboring bubbles.
- Vertical exposed surface ($\theta = 90^{\circ}$): In this case, the natural convection currents rising from the bottom of the container move tangentially to and come in direct contact with the exposed surface. This yields increased heat transfer from the oil to the potato surface already before bubbles appear. In addition, it creates a force which acts upward concurrently with buoyancy leading to a significant total vertical force (known as migration force, Duhar and others 2009). At the side surface orientation, the migration force is perpendicular to the force of the ejected vapor. Bubbles growing at the surface are soon dragged by the migration force and distort their shape, slip on the surface or merge into larger bubbles until they detach. However, detachment occurs perpendicularly to the surface and is therefore mainly controlled by the ejected vapor momentum force. Our visual observations do not allow judging whether bubbles from side surfaces have different size than those emerging at other surface orientations. Nevertheless, natural convection currents and bubble scavenging over the surface yields enhanced mixing of the oil layers in contact with potato surface and therefore boosts drastically heat transfer.
- Horizontal bottom exposed surface ($\theta = 180^{\circ}$): In this case, the exposed surface is in direct contact with the vertical natural convection currents rising from the bottom of the container. This brings in enhanced heat transfer similar to that suggested for the side surface. However, when the first bubbles appear, buoyancy pushes them against the surface not allowing them to

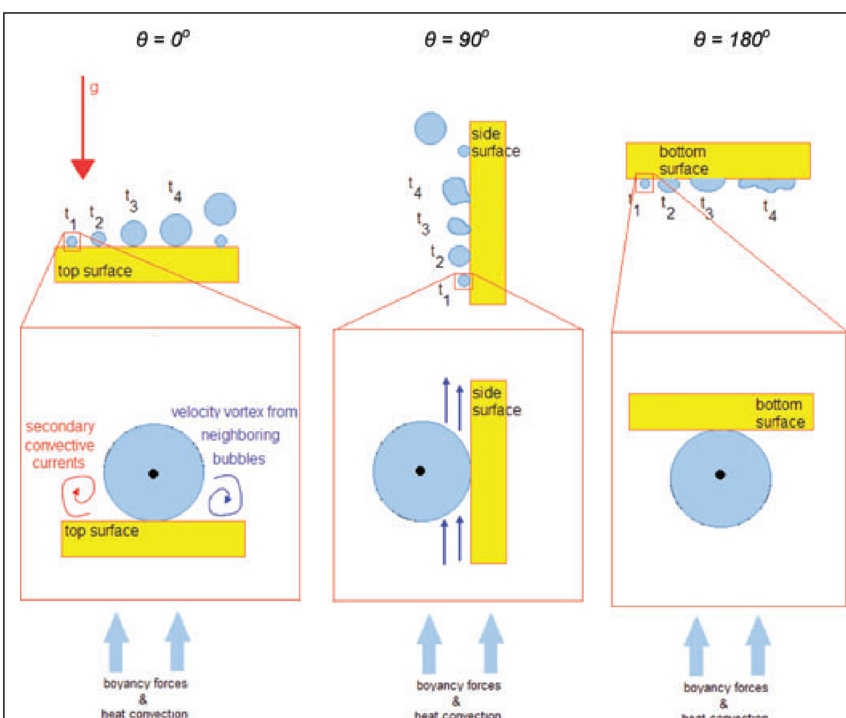

Figure 2–Schematic depiction of bubble behavior on a potato surface at different orientations. The bottom of the oil container (in contact with the hot plate) is further below and outside of the schematic scale.

escape to the oil. These first bubbles consist mainly of dissolved gases and just little vapor as they emerge at temperatures below 100 °C (Lioumbas and others 2012b). In time, more bubbles gather and merge initially to larger bubbles and later to a gas blanket covering a large part of the bottom surface of the potato. This layer acts as an insulator to heat transfer. When the surface eventually reaches 100 °C, boiling starts and it is only then that the ejected vapor breaks the gas layer and allows occasionally some bubbles to escape to the oil.

Temperature profiles in the crust

The temperature profiles obtained during this study for $\theta = 90^o$ and 180^o are compared with the corresponding profiles obtained for $\theta = 0^o$ by Lioumbas and Karapantsios (2012). It is decided to present indicative temperature profiles from individual runs instead of average profiles computed from repeatability runs. Apart from being strict, this avoids smoothing of local features due to inherent variability of samples (Lioumbas and Karapantsios 2012). Figure 3 and 4 present temperature measurements obtained during frying at 150 and 160 °C (Figure 3) and 170 and 180 °C (Figure 4). The T_{oil} profiles attain comparable values in all experiments with the same initial oil temperatures, T_{in}, despite the different orientation. This indicates that similar thermal conditions prevail inside the fryer. Moreover, the temperature inside the potato flesh attains systematically higher values, the closer it is measured to the potato surface. This is indirect evidence that the 3 thermocouples inside the developing crust stay fixed at their prescribed positions. Regardless the orientation of the exposed surface, 2 different regimes can be identified:

A. The *Heating Regime*, which begins as soon as the double trough unit is immersed in the hot oil and finishes when boiling bubbles appear on the potato surface. During this regime, T_{oil} gradually decreases, whereas T_s increases. While for $\theta = 0^o$, T_s increases gradually, for $\theta = 90^o$ and 180^o, T_s increases promptly to a value a little below T_{oil}. This is due to the vertical convective heat currents that rise from the bottom of the fryer and go by the potato surface at $\theta = 90^o$ and 180^o. On the contrary, for $\theta = 0^o$, the potato surface does not come in direct contact with these vertical currents but only with much weaker horizontal currents (see previous section).

The duration of the *Heating Regime* decreases as T_{in} increases (for every surface orientation) because of the higher heat supply to the potato. Nevertheless, surface orientation affects seriously the duration of the *Heating Regime*. Specifically, the duration of the *Heating Regime* is short for $\theta = 90^o$ (for example, 90 s at T_{in} = 150 °C), long for $\theta = 0^o$ (for example, 280 s at T_{in} = 150 °C), and even longer for $\theta = 180^o$ (for example, 540 s at T_{in} = 150 °C). The shorter duration of the *Heating Regime* for $\theta = 90^o$ compared to that for $\theta = 0^o$ can be explained on the basis of the more intense convective heat currents in the former case. However, this cannot explain the even longer duration of the *Heating Regime* for $\theta = 180^o$. In the latter case, the excessively long *Heating Regime* should be attributed to the accumulation of gas bubbles at the bottom surface of the potato before it reaches boiling temperature. The situation is described in the previous section.

B. The *Boiling Regime* of frying begins (designated by the gray stripe in the plots), the moment the first vapor bubble emerges from the potato surface due to surface water evaporation (Hubbard

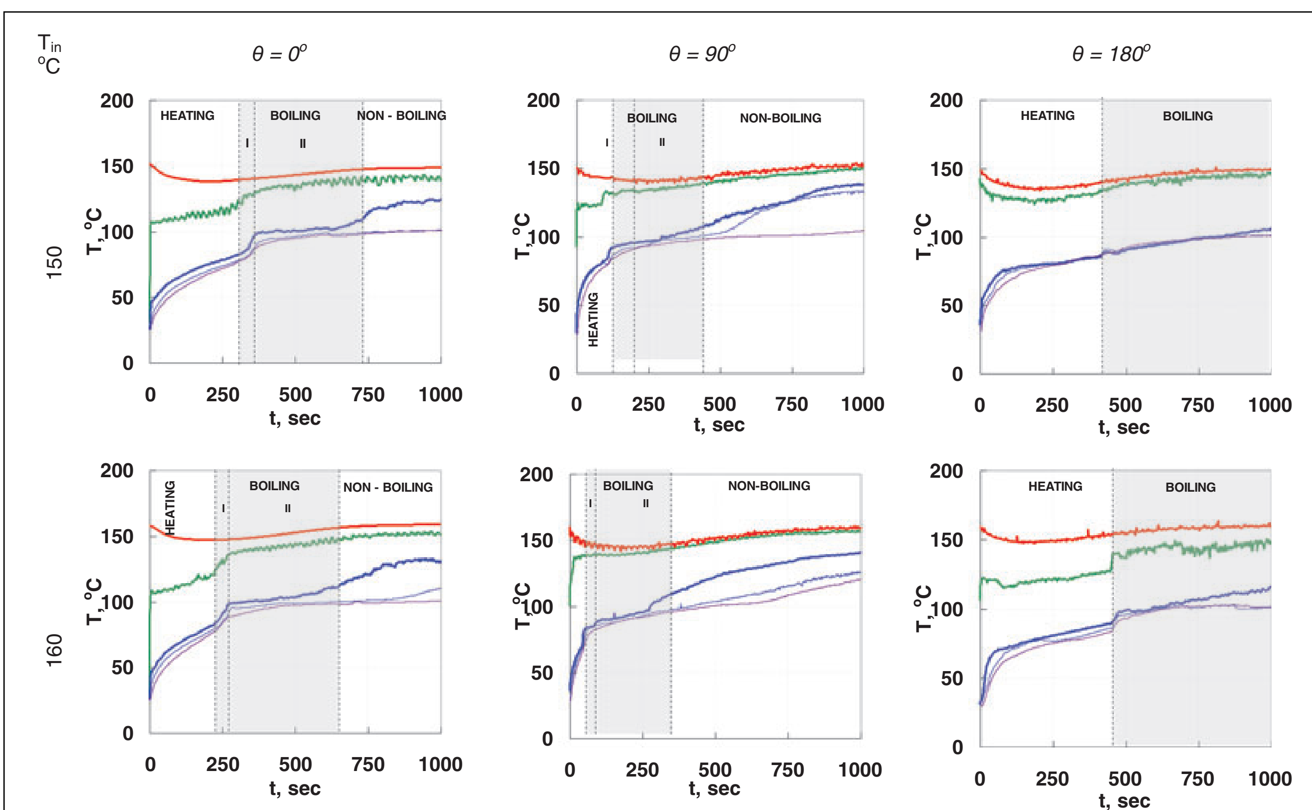

Figure 3–Evolution of temperature distribution inside the crust, T_p, during potato frying (thick blue line, thin blue line, and thin purple line correspond to 0.5, 1.0, and 1.5 mm below the potato–oil interface), on the oil–potato interface, T_S (green line), and inside the bulk oil, T_{oil} (red line) for 3 different surface potato orientations at initial oil temperatures 150 and 160 °C. Data for $\theta = 0^o$ have been taken from authors' prior publication, "Evaporation Front Compared with Crust Thickness in Potato Deep-Fat Frying", J Food Sci 71(1):E17-E25.

and Farkas 1999). This regime ends when bubbles at the potato surface are so scarce and their growth so slow that do not give the impression of boiling anymore (bubble end point). Lioumbas and Karapantsios (2012) have shown that the *Boiling Regime* can be further divided in 2 distinct periods. *Period I* is related with a sharp increase in $T_{0.5}$ profiles due to initiation of surface water boiling (surface at saturation temperature, approximately 100 °C). *Period II* is related with a gradual increase of $T_{0.5}$ profiles due to crust formation and development. The aforementioned behavior for $\theta = 0^o$ is also identified for $\theta = 90^o$ although this becomes more difficult at higher T_{in} values because of the very short *Period I*. As regards the $\theta = 180^o$ case, *Period I* and *II* cannot be distinguished for any examined T_{in} as there is no clear step change in the $T_{0.5}$ profiles. This implies different crust features for $\theta = 180^o$ compared to $\theta = 0^o$ and 90^o (see below).

The duration of the *Boiling Regime* for $\theta = 90^o$ starts sooner and lasts less (for example, approximately 100 and 400 s, respectively, at $T_{in} = 150$ °C) than for $\theta = 0^o$ (for example, approximately 310 and 730 s, respectively, at $T_{in} = 150$ °C). As regards $\theta = 180^o$, the *Boiling Regime* starts much later and its end cannot be easily identified. This is because vapor bubbles from different spots on the potato surface merge to larger bubbles that adhere to the potato surface. Eventually, these bubbles turn into a large vapor layer covering most of the potato bottom surface which is not removed from the potato surface even at long times (that is, 1000 s). Nevertheless, during this period, vapor continues to be generated since small bubbles are noticed to escape occasionally from this large vapor layer.

If someone compares the temperature profiles under the exposed surface of the potato for all 3 surface orientations (Figure 3 and 4), it can conclude that temperatures are, most of the time, higher for $\theta = 90^o$ for all oil temperatures and measurement locations. Intense natural convection currents in the oil rising from the bottom of the fryer are responsible for this. During the *Heating Regime*, temperatures for $\theta = 180^o$ are higher than temperatures for $\theta = 0^o$ because of these intense natural convection currents. The situation reverses during the *Boiling Regime* because of vapor accumulation at the potato's bottom. At $T_{in} = 180$ °C and after *Period I* of the *Boiling Regime* has elapsed, $T_{0.5}$ attains comparable values for $\theta = 0^o$ and $\theta = 90^o$, whereas for $\theta = 180^o$, it takes lower values. Thus, for such high oil temperature, the vertical side surface and the horizontal top surface of a potato experience similar processing intensity during a large part of the frying period.

Evaporation front propagation

Figure 5 presents the estimated propagation of the evaporation front, δ_{ef}, compared with time, for all the examined T_{in} for $\theta = 0^o$, 90^o, and 180^o. The evaporation front propagation data for $\theta = 0^o$ (Figure 5a) were first presented by Lioumbas and Karapantsios (2012) who estimated δ_{ef} from knowledge of the exact location of the measuring thermocouples inside a potato. The evaporation front is designated as the location inside the potato where the temperature is 100 ± 0.5 °C. The ± 0.5 °C band incorporates experimental uncertainty as well as deviations due to local irregularities. This temperature band yields a time band in the plots which becomes wider as δ_{ef} increases. The big dots in

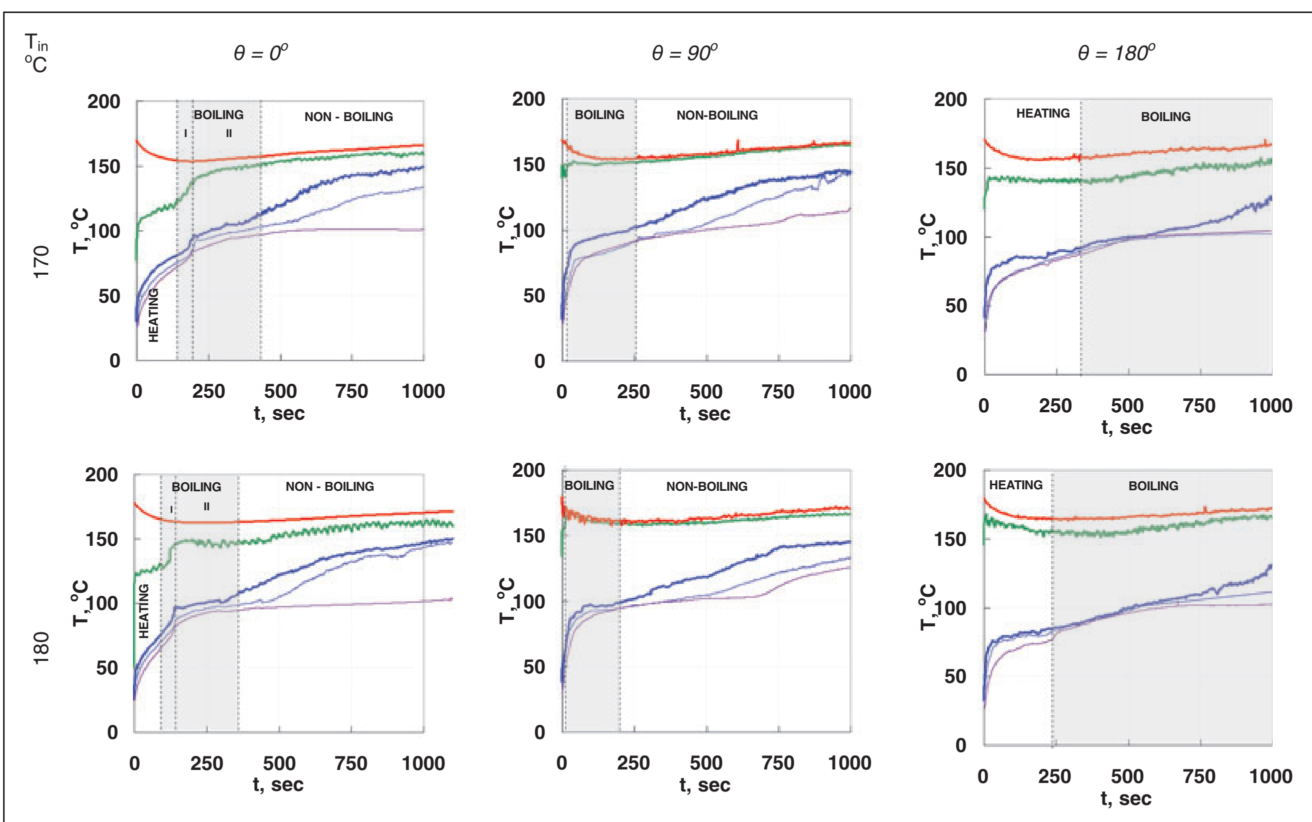

Figure 4–Evolution of temperature distribution inside the crust, T_p, during potato frying (thick blue line, thin blue line, and thin purple line corresponds to 0.5, 1.0, and 1.5 mm below the potato–oil interface), on the oil–potato interface, T_S (green line), and inside the bulk oil, T_{oil} (red line) for 3 different surface potato orientations at initial oil temperatures 170 and 180 °C. Data for $\theta = 0^o$ have been taken from authors' prior publication, "Evaporation Front Compared with Crust Thickness in Potato Deep-Fat Frying", J Food Sci 71(1):E17-E25.

the curves stand for the end of the *Boiling Regime* (bubble end point).

After the immersion of potato in hot oil, evaporation starts at different moments for the different potato orientations: first for $\theta = 90^o$, then for $\theta = 0^o$, and finally for $\theta = 180^o$. This holds for every oil temperature. For $\theta = 0^o$ (Figure 5a) and $\theta = 180^o$ (Figure 5c), evaporation starts sooner at higher oil temperatures. The situation is different for $\theta = 90^o$ where evaporation starts almost right after the immersion of potato in hot oil for all the examined T_{in} except for the lowest one (150 °C). All the above are manifestations of the higher heat transfer rates encountered in the $\theta = 90^o$ case. It is noteworthy that for the 2 highest T_{in} (that is, 170 and 180 °C), δ_{ef} values are much alike for any potato orientation. This indicates that the evaporation front propagation might have reached a maximum limiting rate.

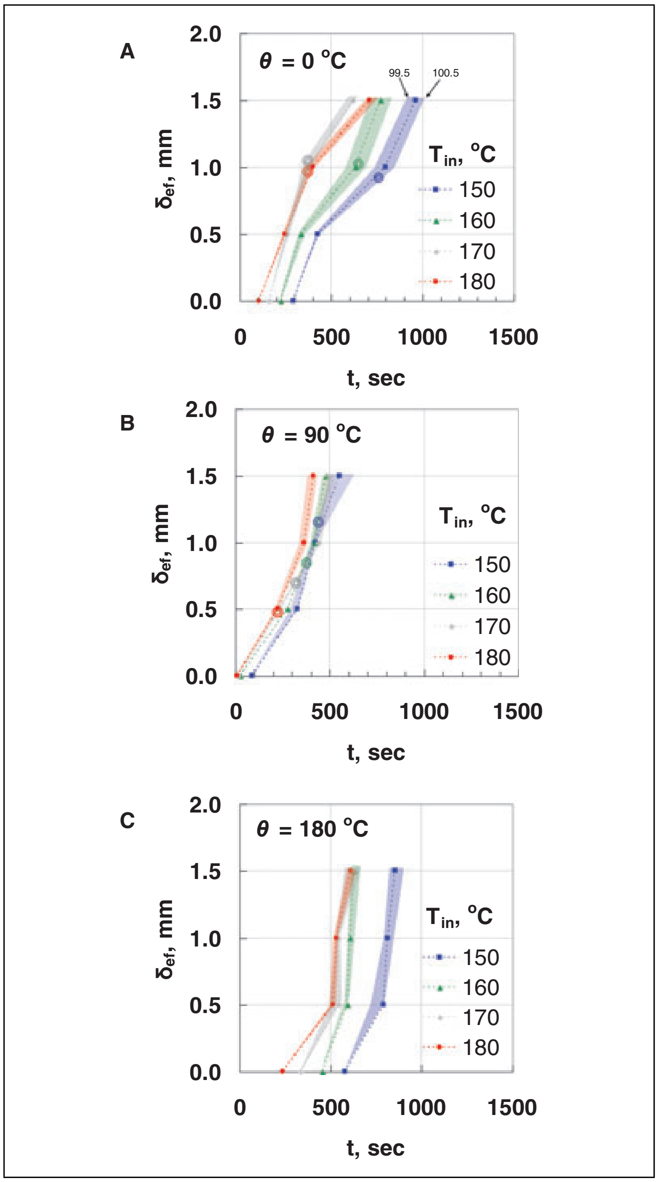

Figure 5–Propagation of the evaporation front, δ_{ef} (designated as the 100 ± 0.5 °C zone) for various initial oil temperatures and different potato surface orientations. The large dots in the curves stand for the end of the boiling regime (bubble end point). Data for $\theta = 0^o$ have been taken from authors' prior publication, "Evaporation Front Compared with Crust Thickness in Potato Deep-Fat Frying", J Food Sci 71(1):E17-E25.

The slopes of the curves differ only a little among runs conducted at different oil temperatures but at the same potato orientation. However, they differ appreciably among runs conducted at different orientations reflecting again the different heat transfer characteristics, and consequently, crust formation. The almost vertical lines for $\theta = 180^o$ and for δ_{ef} between 0.5 and 1.5 mm indicate roughly isothermal conditions among the 3 measuring stations (see Figure 3 and 4) as a result of the fast heat conduction in the potato flesh compared to the slow heat convection from the oil to the potato surface.

The *bubble end point* for $\theta = 0^o$ is reached when the evaporation front has penetrated to approximately 1 mm for all oil temperatures. On the other hand, for $\theta = 90^o$, the bubble end point is reached at progressively shorter times, and accordingly smaller δ_{ef} values, for higher oil temperatures. This implies that while for $\theta = 0^o$, the amount of water loss is comparable among the different oil temperatures, for $\theta = 90^o$, it is smaller for higher oil temperatures. This is attributed to the low thermal conductivity crust region which, as T_{in} increases, appears sooner and is more compact (see below) hindering water evaporation. It is also worthy of noting that δ_{ef} continues to propagate even after the end of vigorous boiling on the potato's surface. No dots are put for $\theta = 180^o$ (Figure 5c), because the *Boiling Regime* continues even after the observation period (1000 s).

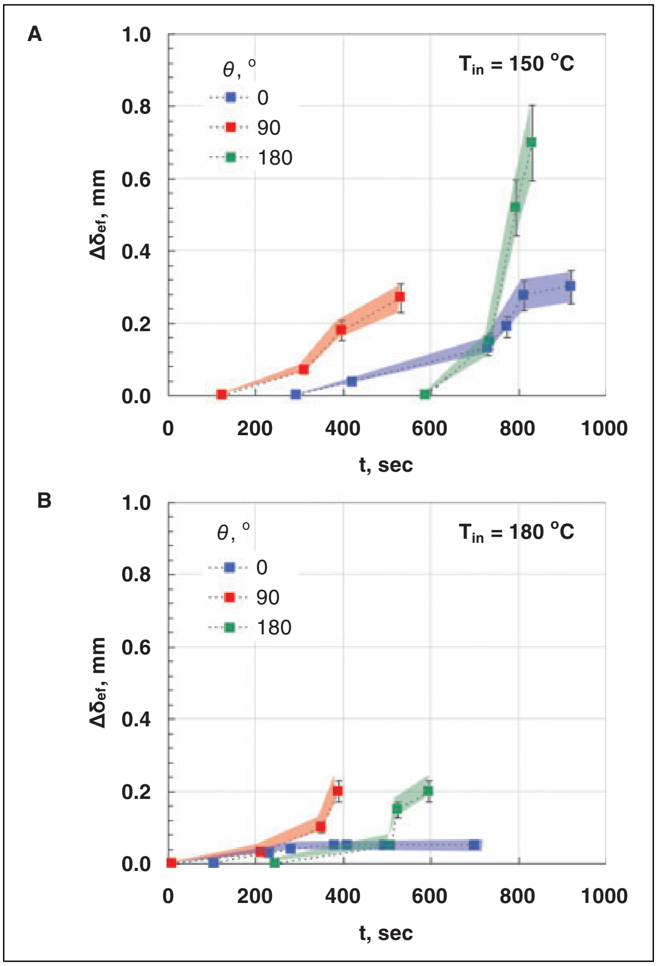

Figure 6–Propagation of the width of the evaporation front zone, $\Delta\delta_{ef}$ (designated as the 100 ± 0.5 °C zone) for various initial oil temperatures and different potato surface orientations. Data for $\theta = 0^o$ have been taken from authors' prior publication, "Evaporation Front Compared with Crust Thickness in Potato Deep-Fat Frying", J Food Sci 71(1):E17-E25.

The concept of a finite evaporation zone instead of a sharp evaporation boundary is not new but has attracted considerable attention lately regarding modeling efforts of frying (Farid 2001; Datta 2007a,b; Farid and Kizilel 2009; Lioumbas and others 2012a). These modeling efforts do not take into account the different heat and mass transfer rates among the different sides of the food. The influence of the potato side orientation on the time evolution of the evaporation front; corresponding to the 100 ± 0.5 °C band,

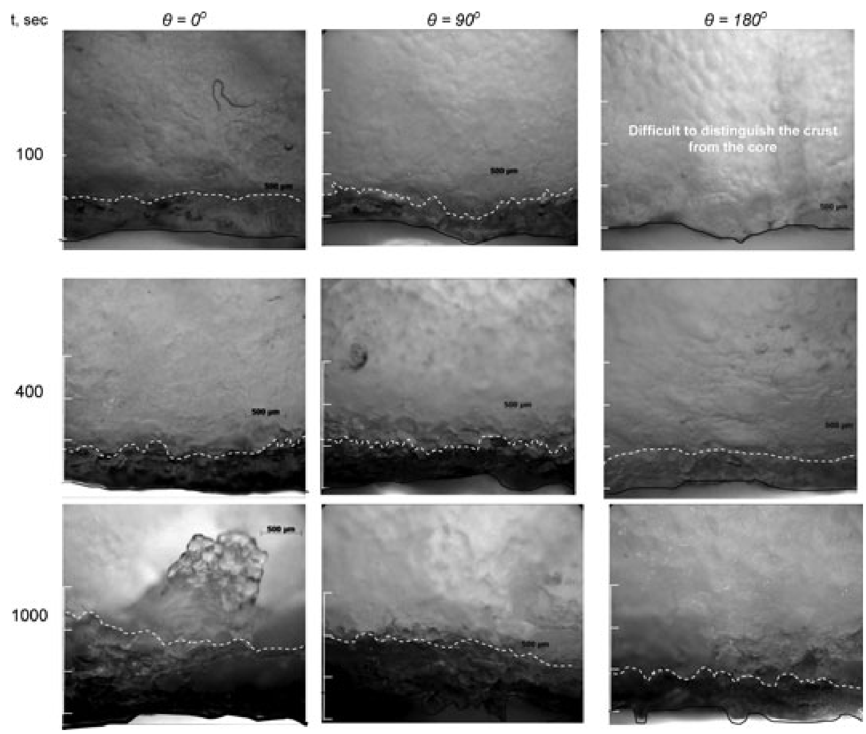

Figure 7–Images of potato's crust taken at different frying times at T_{in} = 180 °C for the examined potato orientations. Data for $\theta = 0°$ have been taken from authors' prior publication, "Evaporation Front Compared with Crust Thickness in Potato Deep-Fat Frying", J Food Sci 71(1):E17-E25.

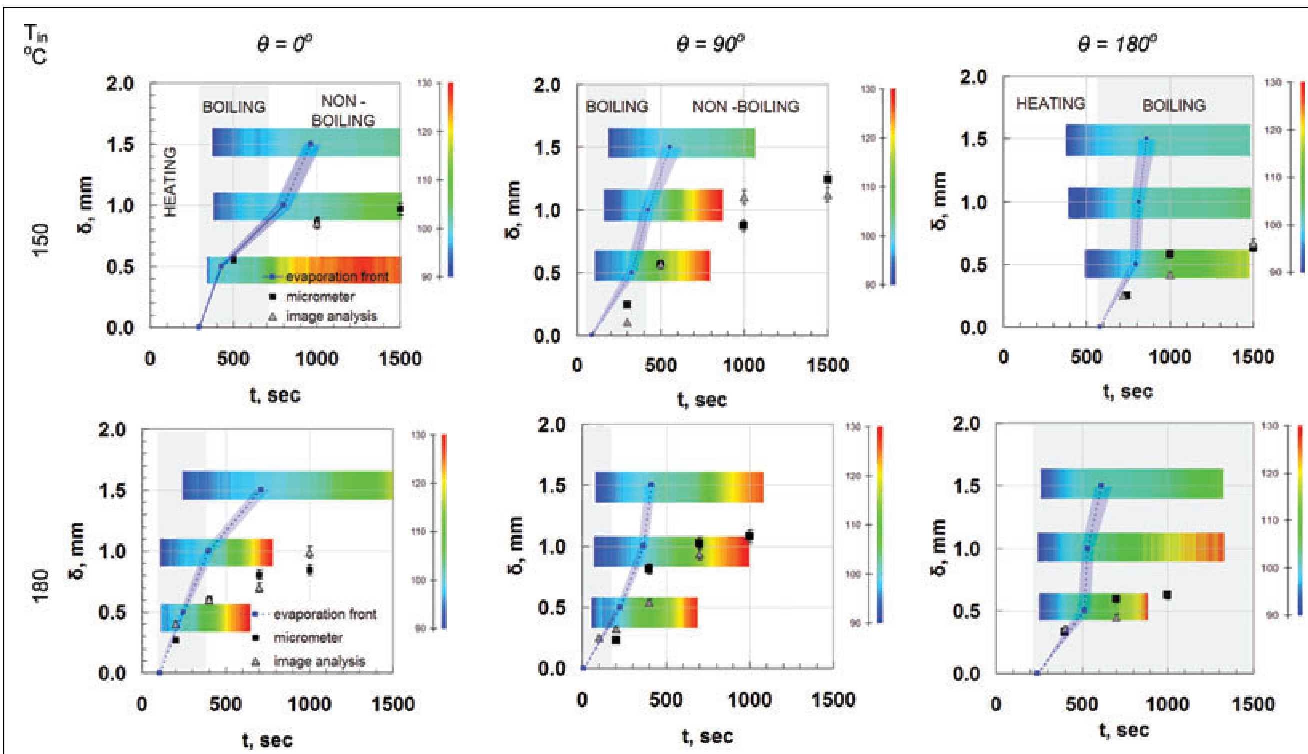

Figure 8–Comparison of crust thickness (measurements carried out with a micrometer and image analysis) with evaporation front propagation, as a function of time, at the examined 3 surface orientations, for initial oil temperatures 150 and 180 °C. The vertical gray stripe denotes the period of intense boiling during frying. The horizontal multicolor stripes represent the temperature evolution at specific regions below potato surface. Data for θ = 0° have been taken from authors' prior publication, "Evaporation Front Compared with Crust Thickness in Potato Deep-Fat Frying", J Food Sci 71(1):E17-E25.

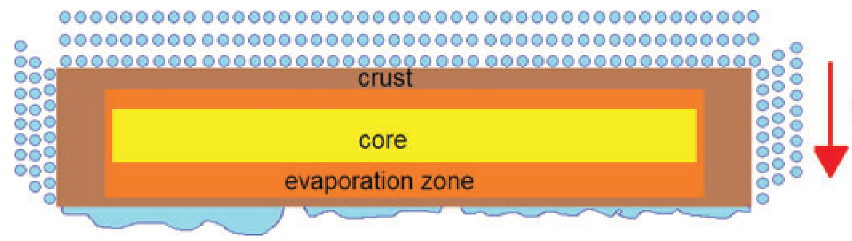

Figure 9–Schematical depiction of the effect of potato surface orientation with respect to gravity on the thickness of the crust and the width of the evaporation zone during deep-fat frying. The bubble pattern observed on each potato surface orientation is also shown.

$\Delta\delta_{ef}$, is presented in Figure 6. It is apparent that $\Delta\delta_{ef}$ is always larger at T_{in} = 150 °C than at 180 °C. This is more so for $\delta_{ef} >$ 0.5 mm where $\Delta\delta_{ef}$ at 150 °C takes several times the value of $\Delta\delta_{ef}$ at 180 °C. Thus, regardless the surface orientation, as the oil temperature decreases, evaporation takes place over an extended zone rather than a sharp interface. It is worth mentioning that for the higher T_{in} values, the width of the evaporation front is rather sharp ($\Delta\delta_{ef} <$ 0.2 mm) regardless the surface orientation. Nevertheless, for the lower T_{in} values, $\Delta\delta_{ef}$ attains almost double values for $\theta = 180^o$ (approximately 0.70 mm) compared to $\theta = 0^o$ and 90^o cases (approximately 0.35 mm). To this end, the above indicate that the width of the evaporation zone is larger for the horizontal bottom surface of food and for lower oil temperature.

Crust thickness evolution

Typical images of potato sticks cross sections fried at 180 °C are presented in Figure 7. Each image corresponds to different frying duration and as such refers to a different sample. The thick black continuous line marks the free surface of the potato, while the white dashed line marks the boundary separating the crust from the core. Despite the fact that the illumination conditions during shooting and the image analysis procedure are identical, the crust exhibits darker colors, and so can be easier distinguished from the core, as T_{oil} and frying duration increase. This is attributed to the formation of a more compact crust, which makes it difficult for light to pass through (Lioumbas and Karapantsios 2012). In this context, the lighter colored crust noticed for $\theta = 180^o$, compared to those for $\theta = 0^o$ and 90^o, indicates also a less compact crust. Orientation has a direct effect on potato texture since it is observed that the crust at the horizontal top ($\theta = 0^o$) and the vertical side surface ($\theta = 90^o$) is crispy, compact, and very dry, whereas the crust at the horizontal bottom surface ($\theta = 180^o$) is soft, pliable, and not so dry. This is in accordance with the findings of Ziaiifar and others (2009). The crust features for bottom surfaces should be attributed to the formation of a gas layer which acts like an insulator preventing high heat fluxes, and therefore, the formation of a very dry rigid crust.

The results of the image analysis along with the micrometer measurements are presented in Figure 8 (the y-bars stand for the standard deviation of each run) along with the evaporation front propagation (Figure 7). Temperature evolution at each measuring station (T_p = 0.5, 1.0, and 1.5 mm) is displayed as a color gradient contour having width equal to the thermocouple tip diameter (0.2 mm). The vertical gray stripe denotes the duration of the *Boiling Regime*. The formation of crust begins right when the *Boiling Regime* begins. Crust thickness continues to increase, though at reduced rates, also during the *non-Boiling Regime*. Moreover, crust thickness seems to attain similar values at the end of the *Boiling* and *non-Boiling Regimes* in both T_{in} although the duration of these regimes is significantly different in the 2 oil temperatures.

For $\theta = 0^o$ and 90^o, the crust thickness hardly exceeds approximately 1.0 and 1.2 mm, respectively, whereas for $\theta = 180^o$, the maximum crust thickness is considerably smaller, that is, 0.5 mm. Lioumbas and Karapantsios (2012) suggested that the crust thickness cannot attain larger values due to the presence of superheated steam in a region ahead of the crust (evaporation front zone) which does not allow complete dehydration of potato flesh. The propagation of the evaporation front follows closely the crust thickness only during the first stage of the *Boiling Regime* regardless surface orientation. As boiling proceeds, the 2 quantities diverge with the evaporation front propagating faster than the evolution of crust thickness. This implies that after a certain time and starting already within the *Boiling Regime*, the evaporated water does not originate exclusively from the dry crust region but also from an evaporation zone beyond it. This zone is widest for $\theta = 180^o$ since the deviation between the evaporation front and crust thickness is largest in this case. Accordingly, the evaporation zone is narrowest for $\theta = 90^o$. The case for $\theta = 0^o$ is intermediate.

What is perhaps of greater significance is that heat and mass transfer phenomena (that is, temperature rise and boiling) are most intense at vertical side surfaces, very mild at horizontal bottom surfaces, and intermediate at horizontal top surfaces. This is in line with the results of Southern and others (2000) and has a direct consequence on energy consumption during deep-fat frying of potato sticks as one can shorten the duration of frying by reducing the extent of horizontal surfaces. Ideally, this could have been achieved if there had been possible to place potatoes at an inclined position (optimally at 45^o) in the fryer. However, it is not realistic to set potatoes at specific inclined positions in the fryer and the usual case is to have them at arbitrary positions and even touching each other. In such cases, even vigorous oil agitation would not be capable of removing bubbles from the extended irregular surfaces created when potatoes touch each other. Slow tumbling of the potatoes inside the oil bath might be a more tempting option as long as the potatoes remain intact.

Conclusion

Novel data reveal the effect of potato orientation on the evaporation front propagation and crust thickness evolution inside the potato. Specifically, it is found that a vertical surface exhibits faster temperature rise (higher heat transfer rates) and more intense boiling phenomena than the 2 horizontal surfaces. From the 2 horizontal surfaces, the bottom surface presents the lowest temperature rise and very mild boiling phenomena. The above have direct consequence to crust thickness. Thus, the crust at the vertical side surface is the thickest, whereas the crust at the horizontal bottom surface is the thinnest. In addition, the former crust is crispy, compact, and very dry, whereas the latter is soft, pliable, and not so dry. Evidence is provided that water evaporation occurs not only from the crust region but also from an extended evaporation zone lying between the crust and the core of the potato. This evaporation zone is wider at the bottom surface, narrower at the side surface, and intermediate at the top surface (Figure 9).

Acknowledgments

This study was carried under the program "Influence of gravity conditions on mass and heat transfer in porous media" funded by esa (Co. No. 22470/09/NL/CBi). The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency. This work is conducted under the umbrella of the COST MP1106 Action: Smart and Green Interfaces—from single bubbles and drops to industrial, environmental, and biomedical applications.

References

Costa RM, Oliveira FAR, Delaney O, Gekas V. 1999. Analysis of the heat transfer coefficient during potato frying. J Food Eng 39:293–9.

Datta AK. 2007a. Porous media approaches to studying simultaneous heat and mass transfer in food processes. I: Problem formulations. J Food Eng 80:80–95.

Datta AK. 2007b. Porous media approaches to studying simultaneous heat and mass transfer in food processes. II: Property data and representative results. J Food Eng 80:96–110.

Duhar G, Riboux G, Colin C. 2009. Vapour bubble growth and detachment at the wall of shear flow. Heat Mass Transfer 45:847–55.

Farid MM. 2001. A unified approach to the heat and mass transfer in melting, solidification, frying and different drying processes. Chem Eng Sci 56:5419–27.

Farid MM, Kizilel R. 2009. A new approach to the analysis of heat and mass transfer in drying and frying of food products. Chem Eng Process: Process Intensification 49(1):217–23.

Farinu A, Baik O-D. 2007. Heat transfer coefficients during deep fat frying of sweetpotato: effects of product size and oil temperature. Food Res Intl 40:989–94.

Hubbard LJ, Farkas BE. 1999. A method for determining the convective heat transfer coefficient during immersion frying. J Food Process Eng 22:201–14.

Lioumbas JS, Karapantsios T. 2012. Evaporation front versus crust thickness in potato deep-fat frying. J Food Sci 71(1):E17–25.

Lioumbas JS, Kostoglou M, Karapantsios T. 2012a. On the capacity of a crust – core model to describe potato deep-fat frying. Food Res Intl 46(1):185–93.

Lioumbas JS, Kostoglou M, Karapantsios T. 2012b. Surface water evaporation and energy components analysis during potato deep fat frying. Food Res Intl 48(1):307–15.

Sahin S, Sastry SK, Bayindirli L. 1999. Heat transfer during frying of potato slices. Lebensm Wiss Technol 32:19–24.

Southern CR, Chen XD, Farid MM, Howard B, Eyres L. 2000. Determining internal oil uptake and water content of fried thin potato crisps. Food Bioprod Process 78:119–25.

Ziaiifar AM, Courtois F, Trystram G. 2010. Porosity development and its effect on oil uptake during frying process. J Food Process Eng 33:191–212.

Ziaiifar AM, Heyd B, Courtois F. 2009. Investigation of effective thermal conductivity kinetics of crust and core regions of potato during deep-fat frying using a modified Lees method. J Food Eng 95:373–8.