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Surface water evaporation and energy components analysis during potato deep fat frying

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Simultaneous, rapid, on-line measurements of moisture loss and temperature of the oil and the potato are employed to depict the major energy components during deep fat frying of potato in a commercial fryer. These components are the latent heat for water evaporation and the sensible heat for oil/potato thermalization. Measurements are found to depend on the examined frying load (i.e. 1/35 and 1/7 $kg_{potatoes}/L_{oil}$) and the initial oil temperature (i.e. 150 and 180 °C) but there is essentially no dependence on the examined oil type (i.e. extra virgin olive oil and refined palm oil). Cross-examination of the major energy components demonstrate that at the early stages of frying it is difficult to determine the latent heat for potato surface water evaporation from the other energy components because of the thermal inertia of the system. Under these circumstances, surface water evaporation at the beginning of frying can be estimated only from analysis of directly measured densely time-resolved moisture loss profiles. These profiles show that surface water evaporation occurs at an unexpected increasing rate. A possible physical explanation is proposed which attributes the observed increasing trend to degassing of potato water.

1. Introduction

Phenomena occurring during deep fat potato frying are extraordinarily complex. Frying involves unsteady heat and mass transfer phenomena in porous media (potato can be considered as such), phase change of water, vapor bubble formation and growth on the food surface, natural heat convection in the oil bulk combined with forced heat convection induced by the violent bubble departure from the food surface (Bouchon, 2009; Mallikarjunan, Ngadi, & Chinnan, 2010; Sahin & Sumnu, 2009). A common practice for the study of frying phenomena in commercial fryers is based on the experimental determination of the temperature profiles inside the potato flesh and in the oil bath assuming that mass transfer (water evaporation and vapor removal from the food) is fast compared to heat transfer. However, the strongly transient thermal behavior of the oil and the fryer's heating elements during the early stages of frying (e.g., Cheevasathianchaiporn & Tangduangdee, 2009) sheds doubt on whether such temperature measurements suffice to describe potato surface water evaporation.

In the majority of works that examine the moisture content change during frying (Table 1), the process is interrupted and potato samples are removed from the oil bath to be weighed (i.e. Chen and Moreira (1997), Sahin, Sastry, and Bayindirli (1999), Vitrac, Trystam, and Raoult-Wack (2003), Farinu and Baik (2008), Baumann and Escher (1995), Costa and Oliveira (1999), Krokida, Oreopoulou, and Maroulis (2000) and Pedreschi, Hernandez, Figueroa, and Moyano (2005)). This approach does not permit a continuous perception of the rapid phenomena that are related to water evaporation during the frying process. This is particularly true for short-living changes occurring right after the immersion of potatoes in the hot oil which are associated with evaporation of potatoes' surface water. Apart from contributing about 4–10% of the total frying energy (Wu, Jouhara, Tassou, & Karayiannis, 2012), knowledge of surface water removal rates is important for setting correctly the boundary conditions for numerical calculations (Fasano & Mancini, 2009). As a matter of fact, surface water evaporation has been less investigated than other aspects of frying, mostly due to unavailability of fast moisture loss data at the onset of frying. Farkas, Singh, and Rumsey (1996) recognized that surface boiling is connected with an increase in surface heat transfer coefficient and inception of crust formation. Bouchon (2009) argued about the transition from surface water evaporation (at low temperatures) to surface water boiling (at saturation temperature). However, a quantitative characterization of surface water evaporation and boiling with respect to experimental moisture loss profiles is missing. Recently, Karapantsios and co-workers (Lioumbas & Karapantsios, 2012; Lioumbas, Kostoglou, & Karapantsios, 2012) provided experimental evidence and theoretical analysis showing the important role of surface water evaporation and boiling on the initial coupling between heat and mass transfer phenomena during deep-fat frying of potato sticks.

To our knowledge, Hubbard and Farkas (1999a, 1999b) were the first and only researchers, who performed *simultaneous on-line*

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Table 1
Frying conditions and methods applied in indicative studies for the convective heat transfer coefficient and water loss determination.

	Reference	Frying conditions		Measurements			Weight	
		Initial oil temperature, T_{in}–Oil bath conditions	Frying Load	Temperature				
				Oil bulk, T_{oil}	Potato center, T_{pc}	Potato surface proximity, T_s	Batch interval	On-line
Water loss determination	Baumann and Escher (1995)	150–180 °C isothermal	20gr of potato slices in 27 L oil	N/A			15–30 s	–
	Costa and Oliveira (1999)	140, 180 °C isothermal	Single pieces of potato slices and French fries in 16 L oil				10 s	
	Krokida et al. (2000)	150, 170, 190 °C assuming isothermal	40 g of French fries in 2 L oil (1:50)				0.3, 0.6, 1.0, 3.0, 5.0, 7.0 10, 13, 15, 20 min	
	Pedreschi et al. (2005)	120, 150, 180 °C isothermal	Ten potato slices in 8 L oil				20 s	
Combined temperature and vapor loss measurements	Costa et al. (1999)	150–180 °C isothermal	5 potato chips and French fries in 18 L oil	–	–	0.3 mm below surface	Image analysis (sampling frequency: not specified)	–
	Sahin et al. (1999)	150, 190 °C isothermal	Single potato stripe in 2.5 L oil	–	–	0.1 mm below surface	15 s	
	Farinu and Baik (2008)	140, 180 °C isothermal	Single sweet potato disk in 2 L oil	–	√	1 mm below surface	25 s	
	Chen and Moreira (1997)	130, 160, 190 °C non isothermal	Approximately 20–50 tortilla chips in 7.5 L oil	√	√	–	10 s	
	Vitrac et al. (2003)	140, 145, 150, 155, 160 °C, non isothermal	30 g of cassava chips in 4.5 L oil	√	√	–	5 s	
	Hubbard and Farkas (1999a,b)	180 °C isothermal	Single Potato disk	–	–	Below surface	–	√
	Present study	150, 180 °C non isothermal	Potato sticks, 1/35 and 1/7 $kg_{potatoes}/L_{oil}$	√	√	–	–	√

weight loss measurements and temperature measurements inside a potato, during deep fat frying of single potato pieces. However, their experimental procedure employed preheating of potatoes to 100 °C in order to eliminate sensible heat transfer in the core region during frying, which is not the actual case in frying. Moreover, the finite size of their temperature sensors (e.g. thermocouples) and the uncertainty regarding their exact placement under the potato surface add ambiguity to the local character of measurements. In addition, Hubbard and Farkas (1999a) focused on frying of a single potato piece (or just a few pieces) assuming constant thermophysical properties of both the oil and the food. However, this does not resemble the conditions encountered in actual applications where many food items fry together resulting in an oil bath temperature drop from 30 to 45 °C (Kalogianni, Karastogiannidou, & Karapantsios, 2009, 2010). This significant oil temperature variation throughout the frying process is expected to affect the thermophysical and physico-chemical properties of both the oil and food. To the best of our knowledge, the only researchers that performed frying experiments with more than one item of food, aiming at the characterization of heat and mass transfer during deep fat frying, are Chen and Moreira (1997) and Vitrac et al. (2003). These researchers studied experimentally frying of tortilla and cassava chips, respectively, which are appreciably different than potato. Moreover, although they performed experiments with more than one food item, their frying loads were significantly lower than those usually encountered in industrial and catering applications.

We were not able to find any study examining in parallel the effects of frying load, type of oil and initial oil temperature on the moisture loss of potatoes and on the temperature evolution of the potato/oil. Even more, it appears that there are no systematic data with regards to *rapid simultaneous on-line* recordings of potato/oil temperature and moisture loss. Therefore, a first goal of the present study is to investigate the relation between moisture loss of potatoes and temperature evolution of the oil and potatoes based on simultaneous, rapid on-line measurements under deep fat frying conditions customary applied to industrial and catering applications. Yet, our chief objective is to employ these measurements to estimate the major energy components during frying and examine whether they are able to depict the short initial frying period associated with surface water evaporation and boiling.

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 various gravity conditions (microgravity, terrestrial and hypergravity conditions). In particular, the present report, describes experiments conducted in the lab under normal gravity conditions which will be used as reference for the underway altered gravity experiments (microgravity, hypergravity). Moreover, this project offers the unique opportunity to modulate gravity and so examine the physical mechanisms of frying under a new fundamental perspective.

2. Materials and methods

2.1. Frying equipment and experimental procedure

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 pre-processed 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 pre-processed potatoes. Fresh potato tubers (Agria variety, all from the same producer, geographical region and harvesting period) were stored and conditioned under regulated temperature and relative humidity as described by Kalogianni et al. (2009). The potato tubers were graded with regards to their specific gravity by putting them in salt solutions of appropriate densities (i.e. salt brine method. Stark & Love; 2003) (the accuracy of setting the salt solution density was better than 0.03%). From the inherent variability tests it was found that 90% of the potato stock had a specific gravity between 1.070 and 1.100 g/cm^3 and only these potatoes were used during frying experiments. The potatoes were cut in sticks ($40 \times 9.8 \times 9.8$ mm^3). The stick dimensions were measured using a digital micrometer (SYLVAC).

Frying experiments were conducted with two oil types (palm oil and olive oil) as it is well known that the oil type dictates the quality of the final product (Bouchon, 2009). Palm oil (refined bleached deodorized palm oil) and extra virgin olive oil were donated by Elais S.A. (Greece). Palm oil was chosen as a common fat for industrial applications (Kalogianni et al., 2009). It has a high content of natural antioxidants of the tocols group which result in a greater antioxidant activity than other vegetable oils (Berger, 2005) during prolonged frying. Olive oil was chosen as a common fat for domestic and catering applications in Mediterranean countries (Kalogianni et al., 2010). A comprehensive list of the most important advantages of frying food with olive oil can be found elsewhere (Sánchez-Muniz & Bastida, 2006). Both types of oil were stored at 10 °C until they are used.

Two initial bulk oil temperatures (150 and 180 °C) and two frying loads (1/7 $kg_{potatoes}/L_{oil}$, 1/35 $kg_{potatoes}/L_{oil}$) were employed. The 1/7 ($kg_{potatoes}/L_{oil}$) frying load is close to the potato-to-oil ratios used in industrial frying whereas the 1/35 ($kg_{potatoes}/L_{oil}$) frying load is common to catering applications. It has been demonstrated that these frying loads lead to significantly different chemical profile of the frying medium (Kalogianni et al., 2009, 2010). The duration of each frying batch was 5 min for both the low and high load. This period was enough to allow a palatable final product.

Apparently, using olive oil for repeated frying and employing a high frying load might not be priority choices for space missions. However, apart from the spin-off value of the project to terrestrial frying applications, examining these parameters allows greater flexibility in selecting proper frying conditions in future space missions. Besides if frying is not repeated many times then the oil negative effects are diminished.

A schematic layout of the devices used during frying experiments is shown in Fig. 1. Frying was performed in a commercial fryer (DELONGHI, F885-DIVA) with a maximum oil capacity of 1.9 L and nominal power of 1800 W. In every frying experiment 1.9 L of fresh oil is used. A controller (adjusted to a small gain to avoid temperature overshoots, BTC 9060, Brainchild Electronic, UK) reduced the delivered power to the fryer inversely proportional to the instantaneous temperature difference from the set point (accuracy ±0.1 °C). During the frying experiments, it was considered important to expose all potato sticks to the same conditions in the fryer. To achieve this, the oil should have uniform temperature across the fryer, and the potato sticks should stay apart (do not contact each other). To ensure oil temperature uniformity, the fryer was furnished with a four-blade stirrer of adjustable speed (0–400 rpm) to agitate the oil. To ensure that the potato sticks stay apart, a special frying basket made of aluminum mesh was built to hold the potatoes firmly but leaving the appropriate space for inserting the stirrer. The basket kept the potatoes away from each other but also did not allow them to float in the oil during the frying process. The basket (diameter approx. 20 cm, height 7 cm) was divided in the vertical direction into four (4) horizontal compartments, each having a height of approx. 1.2 cm (Fig. 1). The potato sticks were introduced in the fryer after the oil has remained in the prescribed initial frying temperature for 10 min. To check the reproducibility of the experiments each frying batch was repeated 5 times.

2.2. Temperature measurement

In order to check whether stirring is necessary to achieve temperature uniformity inside the fryer temperature profiles of the oil bulk, T_{oil}, were monitored by T-type (OMEGA) thermocouples (Ø 1.0 mm) placed at three locations below the oil free surface (i.e. at 1, 2 and 4 cm). These thermocouples were placed far enough from the bubbly region surrounding the frying sticks where the effect of escaping vapor was predominant. The temperature at the potato center, T_{pc}, was measured in a single potato stick per batch, by placing a 0.4 mm T-type thermocouple at the geometrical center of the stick. To avoid errors in the measurement of the potato center, caused by conduction heating along the thermocouple wires, we followed the procedure of Costa, Oliveira, Delaney, and Gekas (1999) who kept one end of the measuring potato just above the oil surface so that thermocouple wires after running through the center axis of the stick exit directly to air. All thermocouples were interfaced to a PC with the aid of a programmable data logger (Data Acquisition Modules — Adam 4018, 16bit A/D board, Advantech). Temperature data were acquired simultaneously at 1 Hz sampling rate.

2.3. Weight measurement

Upon placing the basket with the potatoes into the hot oil, evaporation of water occurs. The loss of water results in a decrease of the total mass of the system. During the frying experiment, the commercial fryer was placed on a top-loaded balance (Kern FKB 8 K0.1 M max. weight 8000, accuracy 0.1 g) to measure on-line the weight loss of water. The balance was interfaced to a PC. The sampling frequency was 1 Hz. In order to close and verify the total mass balance of the system, the weight of the potatoes, m_p, in every experiment was measured separately with a second laboratory balance (Denver instrument, DL-3, max. weight 3000, accuracy 1.0 g) before the potatoes' immersion in the hot oil and after the potatoes removal from the hot oil. It is noted that buoyancy does not affect weight measurements since it is the overall weight of the fryer that is registered and not just the weight of potatoes. The latter would be the case if only the weight of potatoes were measured hanging from a crane scale.

2.4. Statistical analysis

At least 5 records were acquired at all experimental conditions and the reproducibility was excellent. Pearson correlation coefficients

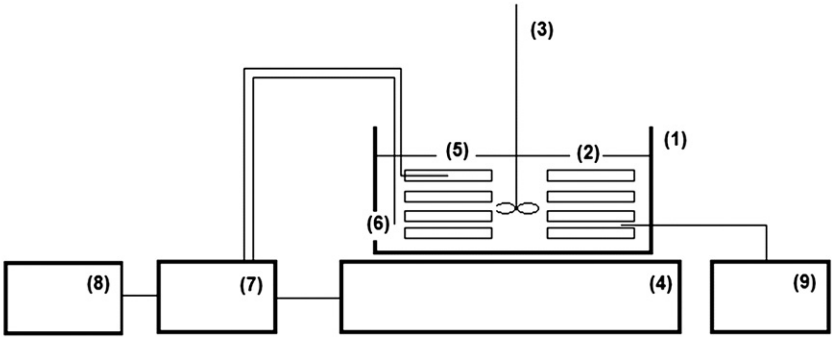

Fig. 1. Layout of experimental setup: (1) Fryer, (2) free surface of frying oil, (3) stirrer, (4) electronic balance, (5) thermocouple mounted at a potato's center, (6) thermocouple immersed in the bulk oil, (7) data acquisition unit, (8) data storage unit, (9) temperature controller.

among sampled temperature and moisture curves were always above 0.97, whereas average instantaneous signal deviations were around 1.5%, a value close to the measured signal's noise.

2.5. Estimation of major energy components

The energy balance which holds during frying is (Cheevasathianchaiporn & Tangduangdee, 2009):

$$Q_{heater}(t) = m_{oil}Cp_{oil}dT_{oil}/dt + dm_{vap}/dt\Delta H_{vap} + m_{pot}Cp_{pot}dT_{pc}/dt + Q_{loss}(t) \quad (1)$$

Q_{heater} (t) and Q_{loss} (t) denote the time-variant energy provided by the fryer according to the employed temperature control scheme and the radiation losses respectively. m_{oil} and m_{pot} stand for the mass of oil and potato respectively, while Cp_{oil} and Cp_{pot} stand for the specific heat capacity of oil and potato receiving values 1.97 and 3.00 J/kg K respectively. ΔH_{vap} stands for water evaporation heat (2257 J/g) and dm_{vap}/dt represents the water evaporation rate. On the right hand side (RHS) of the equation, the first term denotes the sensible heat for the thermalization of oil, the second term denotes the latent heat for water evaporation, the third term denotes the sensible heat of potato flesh and the fourth term denotes the heat losses to the environment. The term representing sensible heating of the crust to temperatures above 100 °C has been omitted since it involves very little energy due to the small size of the crust.

The rapid on-line measurements of moisture loss and of the oil and potato temperatures allow estimation of the different energy terms separately. The estimation of the latent heating of water and of the sensible heating of oil is very accurate since they are computed directly from measurements. On the other hand, the estimation of the instantaneous sensible heating of the potato (through a conduction mechanism) is less accurate. This is because an assumption must be made that the temperature of the potato is spatially uniform so the measured temperature at the center of the potato is equal to the average temperature of the potato. This assumption is good for small Biot number, where convective heat transfer from the oil is low compared to conductive heat transfer inside the potato but worsens as Biot number increases. Even so, this assumption permits an acceptable estimation of potato sensible heating for comparison purposes.

The instantaneous energy provided by the fryer to the oil, $Q_{heater}(t)$, is hard to know during the early stages of frying due to the finite heat capacity and thermal inertia of the heating elements of the fryer (e.g., Cheevasathianchaiporn & Tangduangdee, 2009). In addition, energy losses follow the variability of T_{oil} and are chiefly due to radiation to the environment. Assuming that the oil behaves as a black body with emissivity and configuration factor equal to unity, maximum values of radiation losses can be estimated from the expression $Q_{loss} = \sigma A [(T_{oil})^4 - (T_{amb})^4]$; where σ is the Stefan–Boltzmann constant and A is the area of the emitting body. Estimated maximum radiation losses are around 50 W, showing little dependence on experimental conditions. Thus, energy losses have a minor effect and can be neglected in Eq. (1) at a first approximation.

3. Results and discussion

3.1. Temperature profiles

Fig. 2 presents temperature measurements, T_{oil}, of olive oil during frying at initial oil temperature, T_{in}, of 170 °C and frying load of 1/7 $kg_{potatoes}/L_{oil}$. Data are obtained at different distances (1 cm, 2 cm and 4 cm) below the oil–air interface with no stirring (Fig. 2a) and with stirring at 250 rpm (Fig. 2b). It is shown that:

- The temperature distribution inside the oil can be considered effectively uniform, since the temperature profiles attain pretty similar values at the examined locations. As expected, the largest deviations were between measurements at 1 cm and 4 cm. Even for this worst case comparison, maximum instantaneous deviations are below 3% whereas average deviations are below 2%.

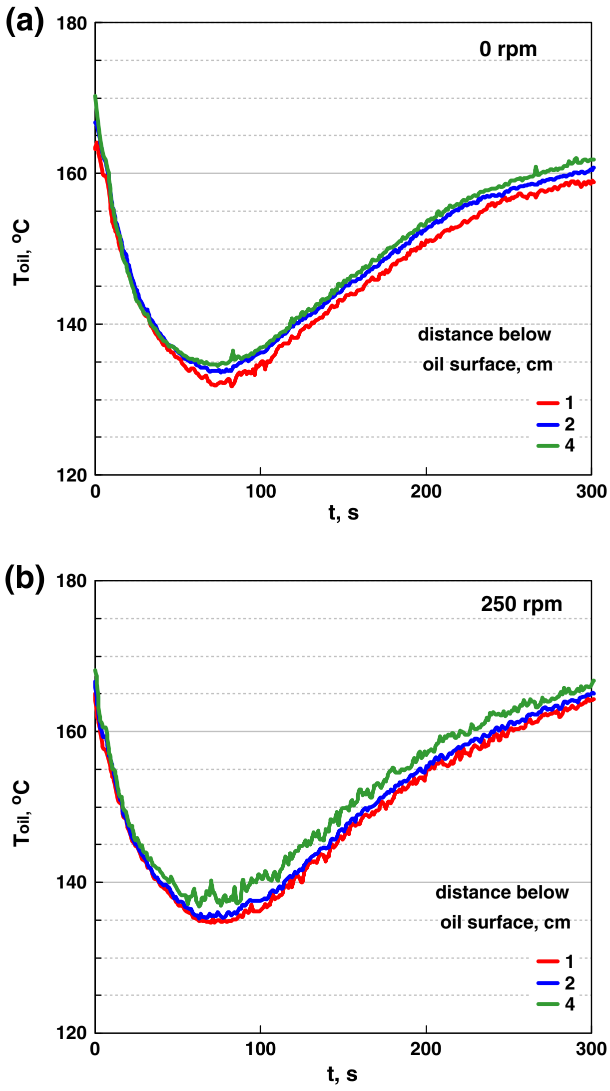

Fig. 2. Bulk oil temperature profiles at different distances below the oil–air interface; 1, 2 and 4 cm correspond to red, blue and green lines. (a) No stirring; (b) 250 rpm stirring.

- The T_{oil} profiles were not significantly affected by stirring. Maximum instantaneous deviations between stirred and unstirred profiles do not exceed 5% whereas average deviations along the whole profiles are less than 2%. Apparently, the agitation induced by bubbling during frying, dominates over the effect of stirring. The latter agrees with the findings of Vitrac et al. (2003).

Based on the above, no stirring was employed during frying whereas the oil bulk temperature was measured by a single thermocouple located at 1 cm below the oil–air interface.

Fig. 3 presents oil temperature, T_{oil}, profiles for the two examined frying loads (i.e. 1/7 and 1/35 $kg_{potatoes}/L_{oil}$) for initial oil temperature 150 °C (Fig. 3a) and 180 °C (Fig. 3b). The impression of noisy values in T_{oil} is because of the displayed y-error bars which stand for the standard deviation of temperature calculated from five repetitions. It is seen that the T_{oil} values decrease right after the potatoes are immersed in the oil bath as also observed by others (e.g. Chen & Moreira, 1997; Vitrac et al., 2003). This cooling effect is due to heat transfer from the hot oil to the potatoes. T_{oil} decreases until the moment the water boiling diminishes and the heat supplied by the fryer's heating elements exceeds the heat demand so T_{oil} rises.

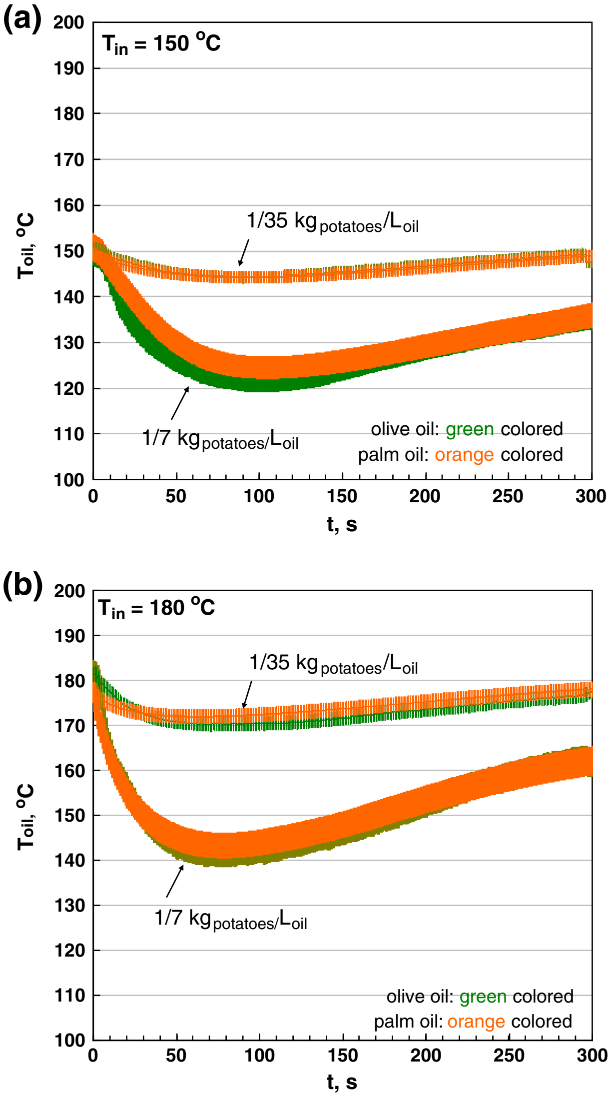

Fig. 3. Temperature profiles of bulk oil for the two examined frying loads; (a) initial oil temperature 150 °C; (b) initial oil temperature 180 °C; the green color stands for olive oil and the orange one for palm oil. The impression of thick lines is due to the applied error bars.

T_{oil} is affected drastically by the frying load. For instance, for olive oil the maximum instantaneous oil temperature drop is 20 ± 3% for a 1/7 $kg_{potatoes}/L_{oil}$ frying load but only 5 ± 0.5% for a 1/35 $kg_{potatoes}/L_{oil}$ frying load. The effect of the initial oil temperature depends on the value of the frying load. At high frying load (1/7) the oil temperature drop is smaller at 150 °C (~18%) than at 180 °C (~23%) whereas at low frying load (1/35) the temperature drop is comparable for the two examined initial oil temperatures (~5%). On the other hand, for the two types of oil (i.e. olive and palm oil) the T_{oil} profiles look alike in all examined conditions: maximum instantaneous deviations between T_{oil} profiles are below ~3% whereas average deviations along the whole profiles are less than ~1%. This is not so surprising since the viscosity of olive and palm oil, which is an important physical parameter that determines the convective heat transfer coefficient due to boiling during frying attains practically the same values regardless the type of oil for the temperature range (i.e. from 130 to180 °C) that frying takes place (Lioumbas, Ampatzidis, & Karapantsios, submitted for publication).

The potato center temperature, T_{pc}, profiles for two frying loads (i.e. 1/7 and 1/35 $kg_{potatoes}/L_{oil}$), two types of oil and two initial oil temperatures 150 °C and 180 °C are presented in Fig. 4a and b. Although the displayed T_{pc} profiles correspond to average measurements computed from five different potato sticks during five repeating experiments, the reproducibility of T_{pc} is excellent (overall imprecision along the curves better than 1%). As soon as the potatoes are immersed in the hot oil, T_{pc} starts rising fast at the beginning and gradually later on and finally levels-off at a plateau value which is slightly above the water boiling temperature at 1 bar (100 °C) but never exceeds 103 °C. This slightly increased temperature above the saturation value is probably the result of a slight overpressure of trapped vapor in the core region of the potato. Apparently, there is no remarkable difference between the profiles obtained for different frying loads and for different types of oil. It is interesting that the T_{pc} profiles are pretty alike for the two different frying loads, despite the fact that the higher frying load corresponds to appreciably lower T_{oil} values. This implies that the temperature at the center of the potato is not significantly affected by conditions prevailing in the bulk oil. The latter argument has been also reached by other researchers who studied the temperature at the center of the potato (Califano & Calvelo, 1991; Chen & Moreira, 1997).

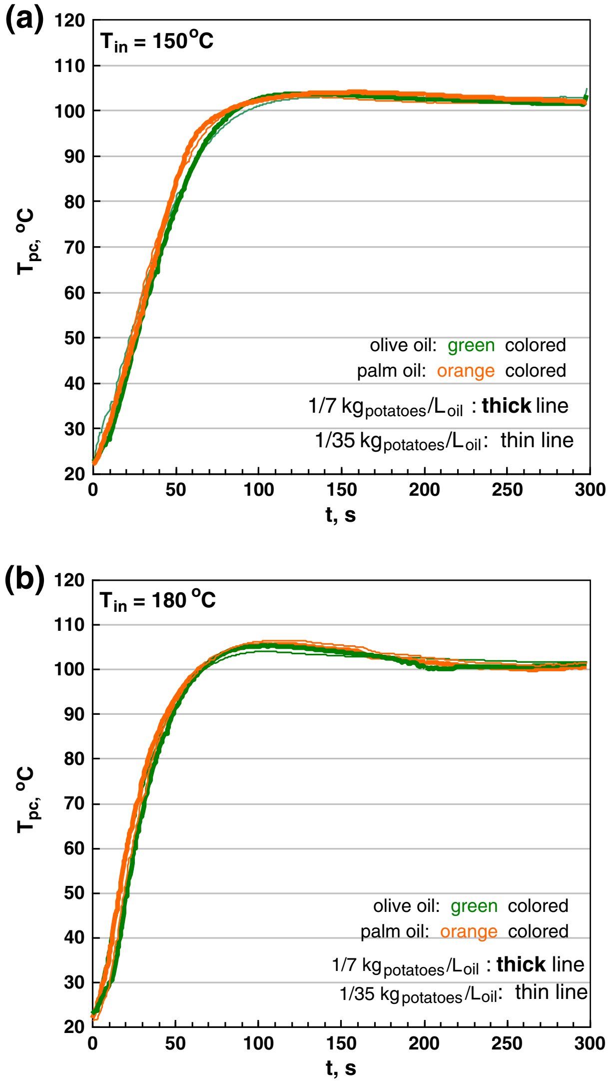

Fig. 4. Temperature profiles at the center of a potato stick for the two examined frying loads; (a) initial oil temperature 150 °C; (b) initial oil temperature 180 °C; the green color stands for olive oil and the orange one for palm oil.

3.2. Moisture loss measurements

As soon as frying begins, potato mass, $m_p = m_w + m_s$, which consists of the sum of the water mass, m_w, and solid mass (dry basis), m_s, is gradually reduced due to water evaporation. The measured potato weight loss profiles during frying at two different frying loads, at two different initial frying temperatures and for two types of oil are presented in Fig. 5. The results correspond to average measurements from five repetitions where the reproducibility of the m_p values is excellent (overall imprecision along the curves ±1%). The remaining potato mass at the end of frying is a bit smaller for a higher initial oil temperature. In other words more water evaporates as the initial oil temperature increases. This is in line with the information presented in Fig. 4.

The estimated average water loss data per stick are shown in Fig. 6 for all the examined frying conditions. We expect that the moisture content among the different potatoes is independent from the potatoes position in the basket since the temperature field in the oil bath is homogeneous (Fig. 2) and there is enough space among the potatoes for hot oil to enter smoothly between them. It is evident that as the frying load decreases and the initial oil temperature increases, the loss of water per stick increases significantly. This is attributed to the higher oil temperatures attained for lower frying loads and higher initial oil temperatures (Fig. 3). Moreover, there is no remarkable or systematic difference between the two types of oil. Thus, the parameter which mainly influences the loss of water is the bulk oil temperature. Since the water loss profiles are virtually not affected by the type of oil, and for the sake of simplicity, only results for olive oil will be presented henceforth.

3.3. Major energy components

Figs. 7 and 8 present the evolution of three major energy components during frying: water latent heat, oil sensible heat and potato sensible heat, for all the examined conditions for $T_{in} = 150$ and 180 °C respectively. Positive values in the plots refer to energy consumption whereas negative values to energy supply. Clearly, water

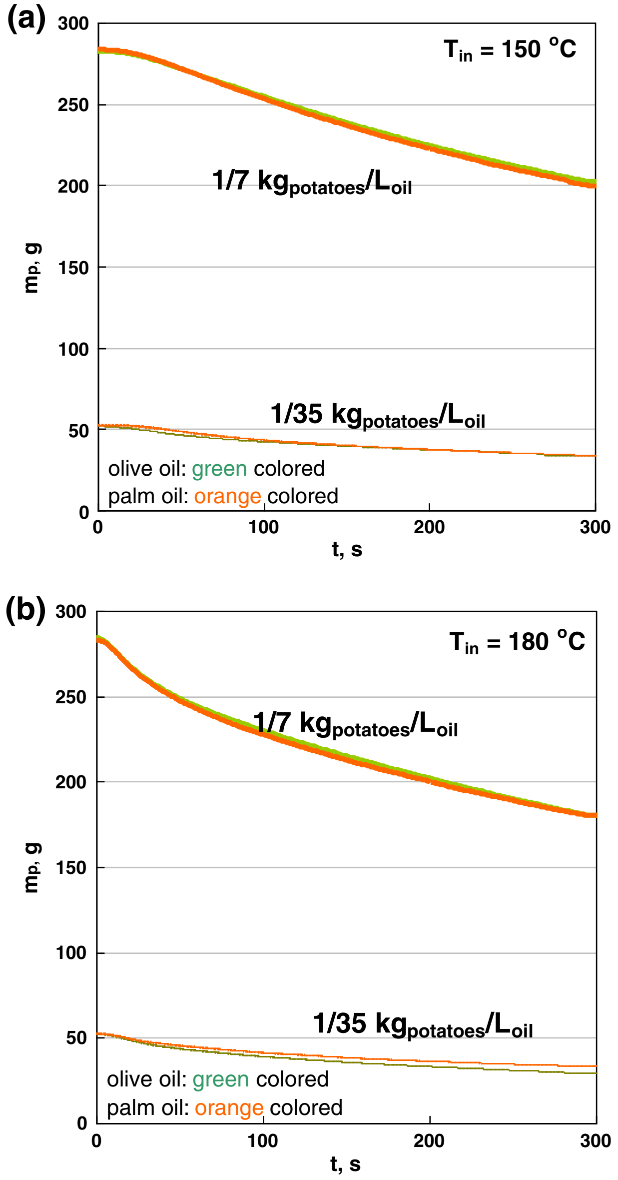

Fig. 5. Potato weight loss profiles during frying at two frying loads; (a) initial oil temperature 150 °C; (b) initial oil temperature 180 °C; the green color stands for olive oil and the orange one for palm oil.

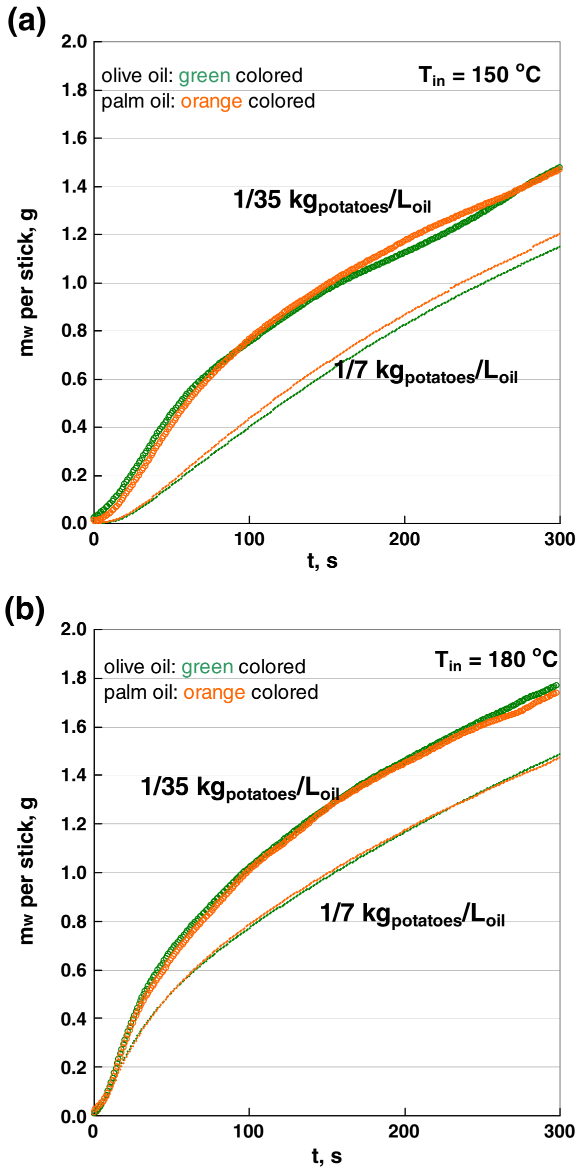

Fig. 6. Average loss of water mass per potato stick during frying at two frying loads; (a) initial oil temperature 150 °C; (b) initial oil temperature 180 °C; the green color stands for olive oil and the orange one for palm oil.

evaporation is overall the most demanding energy consumer in the system. The oil behaves initially as an energy supplier to the system and only later turns to an energy consumer (it crosses the X-axis). This means that the initial frying period is supported partially by the cooling effect of the oil along with the fryer's heat supply. Interestingly, the oil becomes an energy consumer around the moment the sensible heating of the potato vanishes. Sensible heating of potato vanishes when the center of the potato reaches the saturation temperature, ~100 °C.

Fig. 9 displays the sum of the terms in the right hand side of Eq. (1) which equals Q_{heater}. After the ~50 initial seconds, the curves converge into steady state values, different for each frying load. For 1/7 $kg_{potatoes}/L_{oil}$, the average steady state Q_{heater} is ~850 W whereas for 1/35 $kg_{potatoes}/L_{oil}$, the average steady state Q_{heater} is ~170 W. The ratio between these two steady state Q_{heater} values is ~5, as is the ratio of the frying loads. However, the sum deviates severely from the average steady state Q_{heater} values at the early stages of frying where surface water evaporation takes place. The observed negative values indicate that the cooling effect of the oil exceeds the heating effect of the heating elements of the fryer. Bearing in mind the finite heat capacity of the heating elements of the fryer and the applied temperature control scheme, it is difficult to determine the latent heat for potato surface water evaporation from the other energy components of Eq. (1). This is indeed shown in Fig. 10 where the latent heat computed from experimental moisture loss data is compared with estimations based on the energy components of Eq. (1). The agreement between curves is tolerable only at the late stages of frying. In other words, conventional temperature measurements of the bulk oil and potato do not suffice to estimate the latent heat variations at the beginning of frying. Under these circumstances only analysis of directly measured densely time-resolved moisture loss profiles can allow estimation of the initial surface water evaporation period along with the associated amount of evaporated surface water.

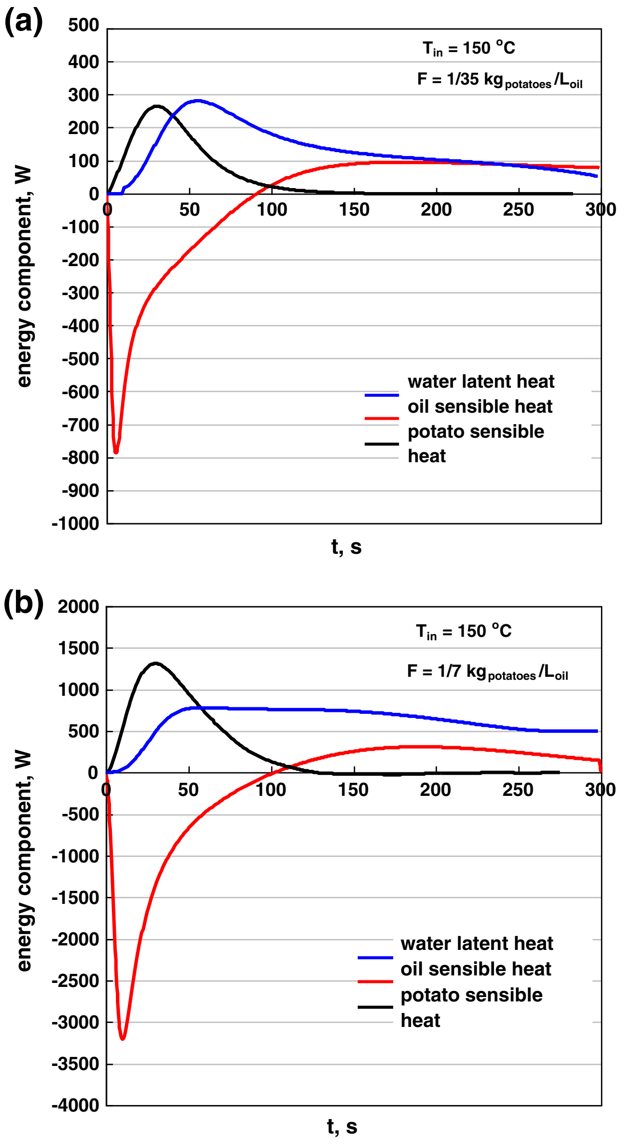

Fig. 7. Evolution of water latent heat, oil sensible heat and potato sensible heat for all the examined conditions for T_{in} = 150 °C for the two examined frying loads; (a) 1/35 and (b) 1/7 $kg_{potatoes}/L_{oil}$.

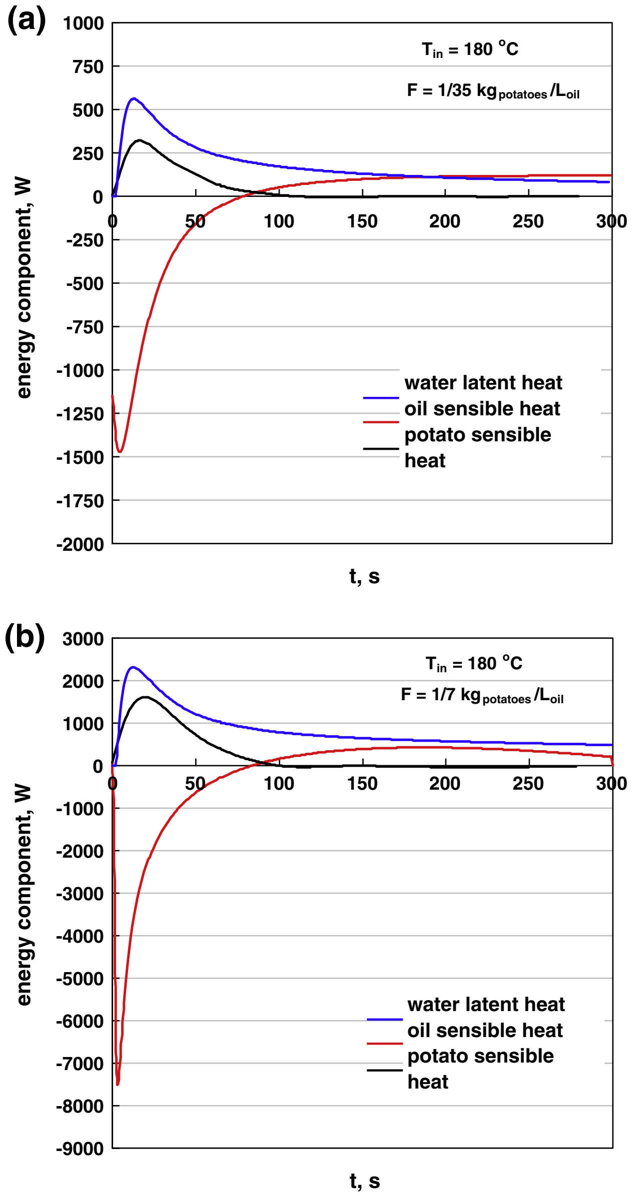

Fig. 8. Evolution of water latent heat, oil sensible heat and potato sensible heat for all the examined conditions for T_{in} = 180 °C for the two examined frying loads; (a) 1/35 and (b) 1/7 $kg_{potatoes}/L_{oil}$.

3.4. Analysis of vapor flux profiles

By assuming that the potato surface area is not changing during frying due to shrinkage, the average vapor mass flux, $F = dm_w/dt/A$,

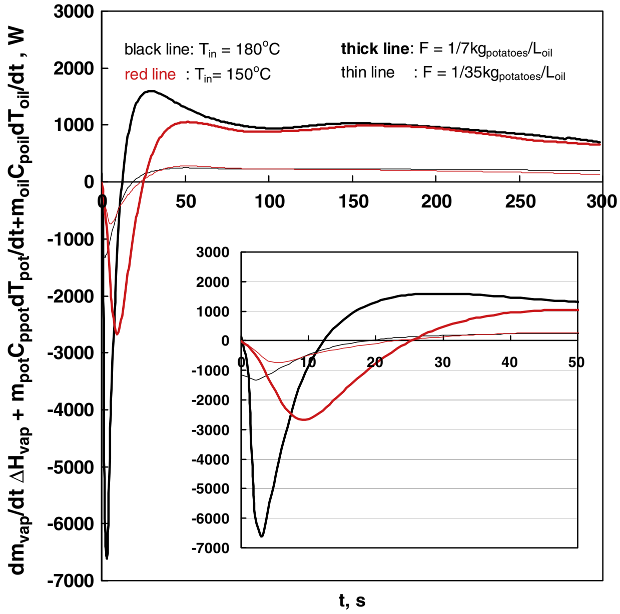

Fig. 9. Evolution of the sum of the terms in the RHS of Eq. (1) which equals Q_{heater}; the small inset plot focus on the early stages of frying.

across the potatoes' surface can be estimated by dividing the measured total water loss rate by the initial surface area of all the potatoes. The estimated vapor fluxes are presented in Fig. 11. As soon as the potatoes are immersed in the hot oil, the vapor flux rapidly increases towards a maximum value and then it starts to decrease. The qualitative behavior of the present vapor flux data agrees with the description of Farkas et al. (1996), who broke the process of frying, after the inception of boiling and before the bubble end-point, into the following periods:

- The surface water boiling period (Period I), characterized by the rapid loss of surface free moisture, the increase of the surface heat transfer coefficient, and the beginning of crust formation.
- The falling rate of moisture loss period (Period II), which represents the period during which most of the moisture is lost, but at a progressively lower rate. It is the longest stage, during which the temperature of the core region approaches the temperature of the boiling point of water.

Vapor flux peaks, $m_{w,\max}$, lie between 13 and 15 s for $T_{oil}=180$ °C and between 55 and 60 s for $T_{oil}=150$ °C. That is, the peak values of the vapor flux, chiefly depend on initial oil temperature and much less on frying load. Furthermore, invoking observations of the crust texture (Lioumbas et al., 2012) one might argue that a sharp peak value is associated with the formation of a rigid dry crust whereas the absence of a sharp peak designates the absence of such crust. At the late stages of frying, the vapor flux values decrease linearly at more or less the same rate (i.e. ~0.01 $g/m^2\ s^2$) in all frying conditions. This is because at the last stages of frying it is evaporation deep inside the potato flesh that dictates water loss.

From the moment of potatoes immersion till the peak in the curves, the calculated total mass of evaporated water per surface area spans between 75 and 140 g/m^2. This corresponds to a surface water concentration range between 3.1 and 6.3% by weight (wet basis) which is in line with other reported values, e.g. Wu et al. (2012). Simple geometrical considerations yield the corresponding range of surface water layer thickness. This is between 90 and 185 μm, respectively. Such thickness values may be related to an average initial surface roughness of the potato surface as a result of the slicing procedure.

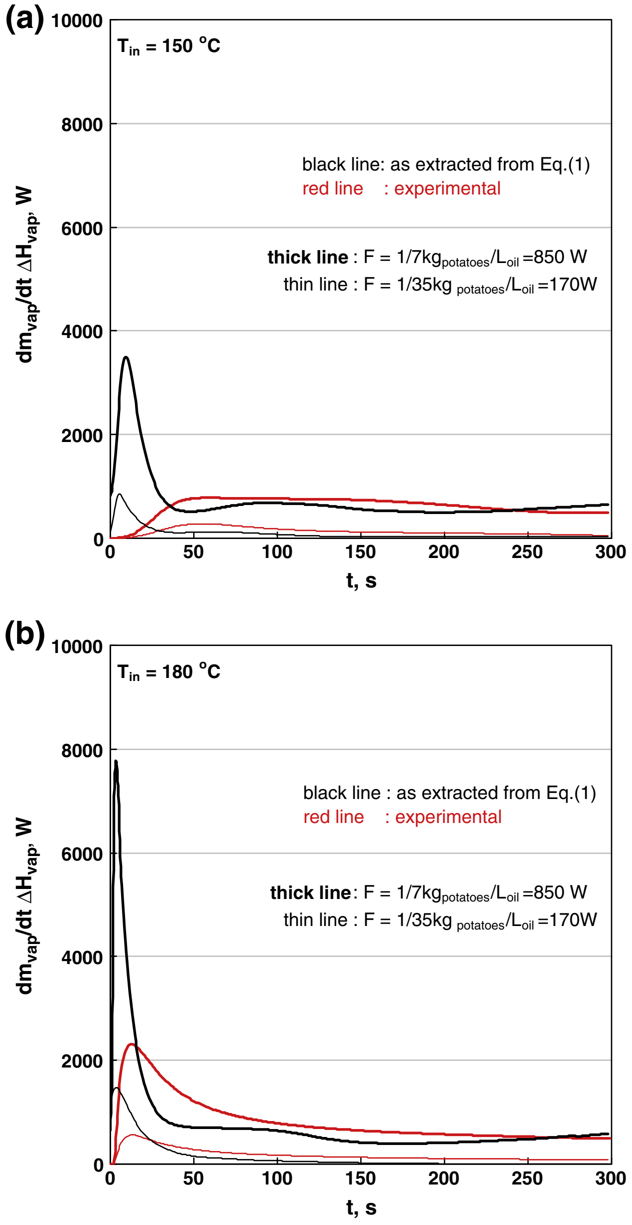

Fig. 10. Latent heat computed from experimental moisture loss data compared with estimations based on the energy components of Eq. (1); (a) initial oil temperature 150 °C; (b) initial oil temperature 180 °C.

It is puzzling that at the beginning of frying the vapor flux profiles show a roughly linear increase with time. This behavior is not consistent with existing evaporation theories according to which surface water should first reach saturation temperature (~100 °C) for vapor bubble formation to begin (Hubbard & Farkas, 1999b). It is reminded that the finite water vapor pressure at temperatures below saturation is not enough to create bubbles; for this a nucleation mechanism is required. Therefore, existing evaporation theories predict that once steam bubbles emerge vapor flux should be constant inasmuch as heat supply is constant. Considering now the observed initial drop of oil temperature, vapor flux should have been even decreasing with time. The behavior described above, however, does not appear in the present experiments but instead an initial gradual increase of vapor flux is observed. After examining several possible conceptual scenarios, we propose the so-called degassing phenomenon as a reasonable physical explanation for the observed behavior. Kostoglou and Karapantsios (2007) and Divinis et al. (2006) have shown that

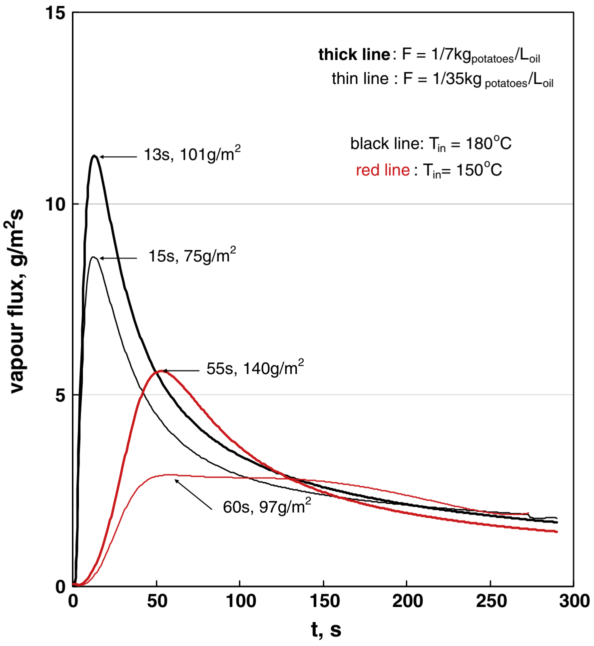

Fig. 11. Experimentally determined vapor fluxes profiles during frying at various conditions.

gas/vapor bubbles can form even at temperatures lower than the boiling point due to desorption of gases dissolved in potato water.

Initial heating renders surface water supersaturated with respect to dissolved gases (being in equilibrium at atmospheric temperature). So, gas nuclei appear on the potato surface and then grow to bubbles (even at temperatures lower than 100 °C). These bubbles contain water vapor in a volume fraction determined by the vapor pressure of water which is an increasing function of temperature. Therefore, as temperature increases the number of bubbles and their vapor content increase. In this way the vapor flux increases, too. Potato surface is rough so the depth of the surface water is non-uniform but follows a distribution. As removal of surface water proceeds, some regions get dry leading to the reduction of evaporation area and accordingly to the reduction of evaporation rate. This may explain the gradual reduction of the slope of vapor flux before the peak (maximum) of the curve. The latter is associated with the onset of crust formation (Farkas et al., 1996).

4. Conclusions

The present experimental data demonstrate that higher initial oil temperatures and lower frying loads result in increased oil temperature profiles which in turn result to higher moisture loss rates. In order to estimate the evaporation of potato surface water at the beginning of frying it is necessary to measure directly moisture loss profiles. The intensity of the measured vapor flux peaks can serve as indicator of the texture of a developing crust. In particular, higher peak values can be associated with a rigid dry crust whereas low peak values can be related with a soft, partially dehydrated, evaporation zone. The similar values of the vapor flux during the last stages of frying among all examined conditions imply that water evaporation occurs deep inside the potato and thus it is unaffected by the conditions prevailing in the oil bath. A simple physical explanation is proposed to explain the unexpected increasing trend of vapor flux values at the beginning of frying based on the mechanism of desorption of gases dissolved in potato water.

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References

Baumann, B., & Escher, E. (1995). Mass and heat potato slices transfer during deep-fat frying of potato slices — I. Rate of drying and oil uptake. *Lebensmittel-Wissenschaft und Technologie*, *28*, 395–403.

Berger, K. G. (2005). *The use of palm oil in frying. Malaysian palm oil promotion council.* 983-9191-02-0.

Bouchon, P. (2009). Understanding oil absorption during deep-fat frying. *Advances in Food and Nutrition Research*, *57*, 209–234.

Califano, A. N., & Calvelo, A. (1991). Thermal conductivity of potato between 50 °C and 100 °C. *Journal of Food Science*, *56*, 586–587.

Cheevasathianchaiporn, W., & Tangduangdee, C. (2009). Mathematical modeling of frying oil temperature during the deep-fat frying process. *Kasetsart Journal Natural Sciences*, *43*, 411–417.

Chen, Y., & Moreira, R. G. (1997). Modelling of a batch deep-fat frying process for tortilla chips. *Transactions IChemE*, *75*, 181–190.

Costa, R. M., & Oliveira, F. A. R. (1999). Modelling the kinetics of water loss during potato frying with a compartmental dynamic model. *Journal of Food Engineering*, *41*, 177–185.

Costa, R. M., Oliveira, F. A. R., Delaney, O., & Gekas, V. (1999). Analysis of the heat transfer coefficient during potato frying. *Journal of Food Engineering*, *39*, 293–299.

Divinis, N., Karapantsios, T. D., De Bruijn, R., Kostoglou, M., Bontozoglou, V., & Legros, J. -C. (2006). Bubble dynamics during degassing of liquids at microgravity conditions. *AIChE*, *52*(9), 3029–3040.

Farinu, A., & Baik, O. -D. (2008). Convective mass transfer coefficients in finite element simulations of deep fat frying of sweet potato. *Journal of Food Engineering*, *89*, 187–194.

Farkas, B. E., Singh, R. P., & Rumsey, T. R. (1996). Modeling heat and mass transfer in immersion frying. II. Model solution and verification. *Journal of Food Engineering*, *29*, 227–248.

Fasano, A., & Mancini, A. (2009). A phenomenon of waiting time in phase change problems driven by radiative heat transfer. *Mathematical Methods in the Applied Sciences*, *32*, 1105–1117.

Hubbard, L. J., & Farkas, B. E. (1999). A method for determining the convective heat transfer coefficient during immersion frying. *Journal of Food Process Engineering*, *22*, 201–214.

Hubbard, L. J., & Farkas, B. E. (1999). Influence of oil temperature on convective heat transfer during immersion frying. *Journal of Food Processing Preservation*, *24*, 143–161.

Kalogianni, E. P., Karastogiannidou, C., & Karapantsios, T. D. (2009). Effect of presence and absence of potatoes under repeated frying conditions on the composition of palm oil. *Journal of the American Oil Chemists' Society*, *86*(6), 561–571.

Kalogianni, E. P., Karastogiannidou, C., & Karapantsios, T. D. (2010). Effect of potato presence on the degradation of extra virgin olive oil during frying. *International Journal of Food Science and Technology*, *45*, 765–775.

Kostoglou, M., & Karapantsios, T. D. (2007). Bubble dynamics during the non-isothermal degassing of liquids. Exploiting microgravity conditions. *Advances in Colloid and Interface Science*, *134–135*, 125–137.

Krokida, M. K., Oreopoulou, V., & Maroulis, Z. B. (2000). Water loss and oil uptake as a function of frying time. *Journal of Food Engineering*, *44*, 39–46.

Lioumbas, J.S., Ampatzidis, C., & Karapantsios, T.D. (in press) Effect of potato deep-fat frying conditions on temperature dependence of olive oil and palm oil viscosity, *Journal of Food Engineering*.

Lioumbas, J. S., & Karapantsios, T. (2012). Evaporation front versus crust thickness in potato deep-fat frying. *Journal of Food Science*, *71*(1), E17–E25.

Lioumbas, J. S., Kostoglou, M., & Karapantsios, T. (2012). On the capacity of a crust–core model to describe potato deep-fat frying. *Food Research International*, *46*(1), 185–193.

Mallikarjunan, P. K., Ngadi, M. O., & Chinnan, M. S. (2010). *Breaded fried foods.* : CRC Press978-0-8493-1461-2.

Pedreschi, F., Hernandez, P., Figueroa, C., & Moyano, P. (2005). Modeling water loss during frying of potato slices. *International Journal of Food Properties*, *8*(2), 289–299.

Sahin, S., Sastry, S. K., & Bayindirli, L. (1999). Heat transfer during frying of potato slices. *Lebensmittel-Wissenschaft und Technologie*, *32*, 19–24.

Sahin, S., & Sumnu, S. G. (2009). *Advances in deep-fat frying of foods.* : CRC Press978-1-4200-5558-0.

Sánchez-Muniz, F. J., & Bastida, S. (2006). *Effect of frying and thermal oxidation on olive oil and food quality.* Olive Oil and Health1-84593-068-1.

Stark, J. C., & Love, L. S. (2003). *Tuber quality, potato production systems* (pp. 329–342). : University of Idaho.

Vitrac, O., Trystam, G., & Raoult-Wack, A. L. (2003). Continuous measurement of convective heat flux during deep-frying: Validation and application to inverse modeling. *Journal of Food Engineering*, *60*, 111–124.

Wu, H., Jouhara, H., Tassou, S. A., & Karayiannis, T. G. (2012). Modelling of energy flows in potato crisp frying processes. *Applied Energy*, *89*, 81–88.