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Effect of potato deep-fat frying conditions on temperature dependence of olive oil and palm oil viscosity

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ABSTRACT

This work investigates how the temperature dependence of oil viscosity varies with the type of frying oil, initial oil temperature, frying load and number of frying repetitions, during potato deep fat frying. Viscosity is measured in small temperature increments over a broad temperature range. A non-linear model is proposed which gives more statistically significant results than other known models in describing the temperature dependence of viscosity. Multiple quasi-linear regression analysis is applied to derive an expression that predicts oil viscosity from important frying conditions such as oil type, frying load, average oil temperature and frying time. For applications where only the initial oil temperature is known, a correlation is proposed for the prediction of the average oil temperature from the initial oil temperature and other frying conditions. The overall accuracy of the model in predicting the temperature dependence of viscosity on the examined frying conditions is better than 95.0%.

1. Introduction

A precise knowledge of the edible oils dynamic viscosity, μ, is a key parameter not only for the optimization of several processes where oil is used (e.g. frying, oil filtration) but also for a rapid appraisal of the oil's chemical composition (oil viscosity increases with the extent of polymerization and with the length of fatty acids e.g., Gertz et al., 2000). Oil viscosity is a function of the measurement temperature, T_m, but this function depends on the intensity of the thermal stresses undergone during processing which can approximately represented by the processing temperature, T_p, (i.e. $\mu = \mu(T_m, T_p)$). Potato deep fat frying is a popular food process where the prevailing conditions such as the initial frying oil temperature, T_{in}, the frying load, F, the duration of a frying batch, t_b, and the number of frying batches using the same oil, B, significantly affect T_p, i.e. $T_p = T_p\,(T_{in}, F, t_b, B)$ (Gertz and Matthäus, 2008; Bouchon, 2009; Sahin and Sumnu, 2009; Mallikarjunan et al., 2010). Apparently, t_b and B can be combined to a single time parameter, t_p, standing for the total duration of processing along batches.

Table 1 shows that the edible fresh oils' viscosity dependence on T_m, $\mu(T_m)$, has attracted the interest of many researchers in the past. To the best of our knowledge, only Fasina and Colley (2008) provided systematic experimental evidence of $\mu(T_m)$ profiles over a broad temperature range (i.e. 40–180 °C). As regards fried oils, we are aware only of the work of Bansal et al. (2010) that claims to have measured $\mu(T_m)$ profiles in a wide temperature range; i.e. 40–180 °C, although it does not present any $\mu(T_m)$ profile. Furthermore, that study examined the effect of repeated frying batches on μ keeping constant other frying conditions, such as F and T_{in}. In both the aforementioned studies, the sporadic viscosity measurement every 10–20 °C did not allow obtaining dense data series that would increase the confidence in statistical testing of models.

It is well known that the intensity of the heating process is the most important parameter for the quality of the final product in frying process (Zhang and Zhang, 2007). Recently, Franke and Strijowski (2011), performed meticulous frying experiments with a variety of commercial fryers and showed that the specific heating power of the fryer, Q/L_{oil}, frying load, initial oil temperature and frying time, significantly influence the browning of the food (indicator for acrylamide formation amongst others). These authors reported a substantial drop of the initial oil temperature during frying which varies with the process parameters. So, at first glance it looks odd that the initial oil temperature was successfully used in their model instead of the average oil temperature during frying (a real measure of the imposed thermal stresses). This implies that the average oil temperature can be adequately described by the other process parameters in the model, offering thus the convenience of using the readily available initial oil temperature value when applying the model. Linking the above arguments to our viscosity concerns, it is interesting that we could not locate any published work that associates the viscosity of frying oils with the transient temperature profiles or even the average oil temperature during frying.

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Table 1
Selected papers from literature indicating the current state of knowledge in the field.

	References	Test conditions					Viscosity	
		Initial frying oil temperature, T_{oil}, °C	Frying load, F, $kg_{potatoes}/L_{oil}$	Frying time, t, min	No. of oil types	Oil Thermal stress	$T_{measuring}$, °C range, (step)	Model (In bold best proposed)
Fresh oils	Lang et al. (1992)	N/A			6	NO	4–100	Empirical
	Tseng et al. (1996)				1		25–190 (3)	Arrhenius
	Abramovič and Klofutar (1998)				7		25–55 (10)	Arrhenius, empirical
	Bheemreddy et al. (2002)				1		25–180 (20)	empirical
	Fasina et al. (2006)				12		5–95	Arrhenius, WLF, power law
	Narváez et al. (2008)				1		50–100 (10)	Andrade, empirical
	Debnath et al. (2012)				5		170, 180, 190	Arrhenius
	Fasina and Colley (2008)				11		35–180 (15–20)	Arrhenius, WLF, power law
	Bonnet et al. (2011)				4		10–50 (5)	Arrhenius
	Present study				2		30–180 (1) 40–180 (1)	Arrhenius, Andrade, WLF, empirical
Fried oils	Bheemreddy et al. (2002)	?	?	?	1		25–180 (20)	Empirical
	Tseng et al. (1996)	190	?	1	1	Up to 60 h (10 h step)	25–190 (3)	Arrhenius
	Santos et al. (2005)	190	0	N/A	8	Up to 8 h	25	–
	Kim et al. (2010)	170	?	1	7	1 batch	20–70 (5)	Arrhenius
	Bansal et al. (2010)	182.5 ± 2.5	1/50	3–4	1	45 batches	40–180 (10)	-
	Chatzilazarou et al. (2006)	175	1/20	6	2	25 batches	25	-
	Sánchez-Gimeno et al. (2008)	170	1/20	3	2	60 batches	20	-
	Kalogianni et al. (2010)	182	1/7, 1/35	12, 3	2	40 batches	50	-
	Present study	150 180	1/7, 1/35	5	2	40 batches	30–180 40–180 (1)	Arrhenius, Andrade, WLF, empirical

The objective of the present study is twofold. First, to provide experimental evidence on the influence of various frying conditions, such as oil type, T_{in}, F, and t_p on $\mu(T_m)$ profiles. The $\mu(T_m)$ profiles are determined with a very small temperature increment ($\Delta T = 1$ °C) over a wide temperature range ($T = 30$–180 °C). Second, to propose an empirical model for the temperature variation of viscosity over the employed temperature range that gives more accurate predictions than other known models in literature. An additional criterion for the selection of the present model is to allow satisfactory correlation of its parameters with frying conditions which is of great value for engineering applications.

2. Material and methods

2.1. Frying equipment and experimental procedure

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 Lisińska and Gołubowska (2005). It must be stressed here that our interest is on direct frying of raw potatoes since frying of raw potatoes can serve as reference for comparisons in subsequent work with pre-processed potatoes. The potato tubers were graded with regards to their specific gravity by putting them in salt solutions of appropriate densities (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). 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 and Bastida, 2006). Both types of oil were stored at 10 °C until they are used.

Frying was performed in a commercial fryer (DELONGHI, F885-DIVA) with a maximum oil capacity of 1.9 L and nominal power, Q, 1800 W. All frying series started with 1.9 L of fresh oil in the fryer. Oil samples (100 ml) were collected at the beginning (fresh oil) and after every 10 frying batches, i.e., at the 0th, 10th, 20th, 30th and 40th batches. Therefore, the volume of oil, L_{oil}, decreased after every 10 batches, due to sampling of oil but also oil absorption from the potatoes. The oil was not replenished between frying batches so in order to keep the frying load constant through the 40 batches, the mass of the potatoes in the fryer was reduced accordingly. In other words, after every 10 batches the total volume/mass of oil/potatoes in the fryer was decreased. To suppress the effect of the specific heating power of the fryer, Q/L_{oil}, on the frying process and so minimize the deviation in the oil temperature profile after every other 10 batches, an external controller (BTC 9060, Brainchild Electronic, UK; adjusted to a small gain to avoid temperature overshoots) was employed to reduce the

delivered power to the fryer inversely proportional to the instantaneous temperature difference from the set point (accuracy ± 0.1 °C). Oil, samples were kept at −26 °C, under a nitrogen atmosphere, in air-tight closed, dark-color glass bottles. Before analyzing the samples, they were left to reach ambient temperature and then they were conveniently homogenized.

During the frying experiments, it was considered important to expose all potato sticks to exactly 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. The reproducibility and the homogeneity of the temperature field inside the oil bath were ensured by on-line oil temperature recordings (sampling rate: 1 Hz) at several locations inside the fryer with T-type thermocouples (average instantaneous temperature deviations among three repetitions were around 1.0%, a value close to the measured signal's noise). 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. The potato sticks were introduced in the fryer after the oil has remained in the prescribed initial frying temperature for 10 min.

The conditions of the repeated frying experiments were selected in such a way to allow a considerable (also realistic for industrial and catering applications) change in the chemical profile of the frying medium (Kalogianni et al., 2010, 2011). Two frying loads were employed: i.e. $F_1 = 1/7$ $kg_{potatoes}/L_{oil}$; which resembles the potato-to-oil ratios used in industrial scale and $F_2 = 1/35$ ($kg_{potatoes}/L_{oil}$); which is common to catering applications (Kalogianni et al., 2009). Two initial bulk oil temperatures (150 and 180 °C) were employed. A set of eight series of repeated frying experiments were conducted (2 frying loads × 2 initial temperatures × 2 types of oil = 8 series). Every series consisted of 40 consecutive frying batches, each batch lasting 5 min. The total time that the oil was kept at elevated temperatures, t_p, was 5 h (continuous) including the time needed for heating up the oil before frying and the time in-between frying batches. All experiments were repeated three times. Table 2 summarizes the experimental settings described in this section.

Table 2
Experimental settings taken into account for the computation of a and b parameters.

Parameter	Value
Initial oil temperature, T_{in}, °C	150, 180
Average oil temperature, T_{ave}, °C	$130 < T_{ave} < 175$ (32 distinct values)
Frying load, F, $kg_{potatoes}/L_{oil}$	1/35, 1/7
Frying duration, t_p, min	50, 110, 170, 230 (for the 10th, 20th, 30th and 40th frying batch)
Fryer's specific heating power, Q/L_{oil}, kW/L	1.0, 1.4, 2.1, 3.3 (for the 10th, 20th, 30th and 40th frying batch)
Type of oil, TYPE	olive oil (TYPE = 0), palm oil (TYPE = 1)

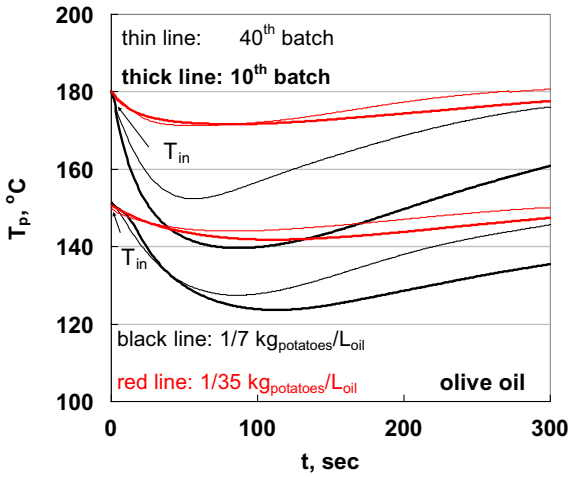

Fig. 1. Temperature of olive oil during frying at high (1/7) and low (1/35) frying load ($kg_{potatoes}/L_{oil}$), at 150 °C and 180 °C initial frying temperatures and for the 10th and the 40th frying batches (average instantaneous T_p deviations ~±1.0% calculated from three repetitions).

2.2. Viscosity measurements

Dynamic shear viscosity measurements were conducted with a MCR 301, TruGap®, Anton Paar cone-plate rheometer (CP50-1/TG, cone angle: 0.982°, plate diameter: 49.964 mm, truncation: 49.0 μm; volume of oil used for viscosity measurements 0.57 ml). Initially, the possibility of oil samples to attain a non-Newtonian rheological behavior (with respect to shear rate) upon repeated frying was examined at two different temperatures (i.e. 50 and 150 °C) at shear rates varying from 10 to 1000 s^{-1}. The major set of measurements of the temperature dependence of oils viscosity was performed at a shear rate 200 s^{-1} for a temperature range from 30 °C (olive oil) and 40 °C (palm oil) to 180 °C (increment $\Delta T = 1$ °C). The rheometer provides viscosity measurements with ±0.1% accuracy controlling the sample's temperature with a Peltier bottom plate and a thermally regulated hood accessory.

The value of the sample heating rate is a serious matter of concern. Heating rate should not be too slow to avoid oil degradation due to prolonged exposure to heat (over and above the degradation caused by frying itself) but also not too fast in order for the sample to follow the prescribed temperature profile in the sample holder. To check the above, viscosity measurements were performed at different heating rates and were compared to steady state measurements at 50 and 150 °C. The best compromise out of this comparison was a heating rate of 5 °C/min which showed a good agreement (i.e. better than 1.0%) between dynamic and steady measurements. The selected heating rate corresponds to 6 min for spanning a temperature range of 30 °C, which corresponds to the maximum oil temperature drop during deep fat frying (Fig. 1). Therefore, insignificant oil degradation is expected to occur during viscosity measurements. All tests were performed twice aiming to check reproducibility. The maximum deviation among all replicates is smaller than ±1.0% (average deviation ±0.75%).

2.3. Statistical analysis

Non-linear regression analysis of μ versus T_m data was conducted using TableCurve® software which searches through a library list of over 3,000 equations. Then, multiple quasi-linear regression analysis was used to correlate the coefficients of the derived non-linear expression with frying parameters such as type of oil, frying load, oil temperature and time. The statistical significance of each coefficient was tested using the t-test with $P > 0.95$ (Draper and Smith, 1981). For the determination of the best regression equation a stepwise backward elimination procedure was employed: the coefficient with the lowest significance below the threshold was removed and the approach was recalculated with

the remaining coefficients. This procedure was repeated until the significance of each of the remaining coefficients in the approach was above the threshold. Regression analysis was conducted using the Microsoft® Excel™ plug-in Analyse-it®.

3. Experimental results

3.1. Oil temperature measurement

Fig. 1 presents typical olive oil temperature profiles, $T_p(t)$, obtained at various frying conditions. It is apparent that the oil temperature drops from its initial value, T_{in}, as soon as the potatoes enter the hot oil. The extent of the temperature drop is greater at higher initial oil temperature, T_{in}, and frying load, F, and at lower frying batch, B. One might have expected smaller deviations in the temperature profiles between cases because of the employed external controller in the fryer. However, the thermal inertia of the system (its response time to adopt thermal restoring actions) proved much stronger than its heat capacity. This implies that the heat supply unit of the fryer is not capable of delivering energy as fast as it is required to maintain a set frying temperature. Evidently, the situation would be worse without the controller. Keeping the above in mind, it is apparent from Fig. 1 that the intensity of the frying process can not be satisfactory described by the initial oil temperature but rather by the average value of the oil temperature profile during a frying batch. Multiple quasi-linear regression analysis between the average (over the duration of the 5 min long frying batches) oil temperature, T_{ave}, and the other frying parameters employed in this study, yields an expression which shows that T_{ave} of each frying batch is significantly ($P > 0.95$) affected by T_{in}, Q/L_{oil} and the initial mass of potatoes, $m_{potatoes}$ used in that frying batch.:

$$T_{ave} = 25.2 + 0.8738T_{in} - 3.68Q/L_{oil} - 99.17m_{potatoes} r^2 = 0.992 \quad (1)$$

The statistically significant role of Q/L_{oil} and $m_{potatoes}$ in describing T_{ave} is in line with the findings of Franke and Strijowski (2011) regarding their specific energy consumption for water evaporation. The absence of the frying time parameter in Eq. (1) indicates that T_{ave} is not so much affected by the gradual degradation of oil through repeated batches.

3.2. Check for non-Newtonian behavior

Fig. 2 presents the shear stress, σ, measured at 50 and 150 °C for olive oil and palm oil over a shear rate, γ, range between 10 and 1000 s^{-1}. The examined samples are those after 40 repeated frying batches where the highest degradation of the oil has occurred. Samples are from runs conducted at both examined frying loads

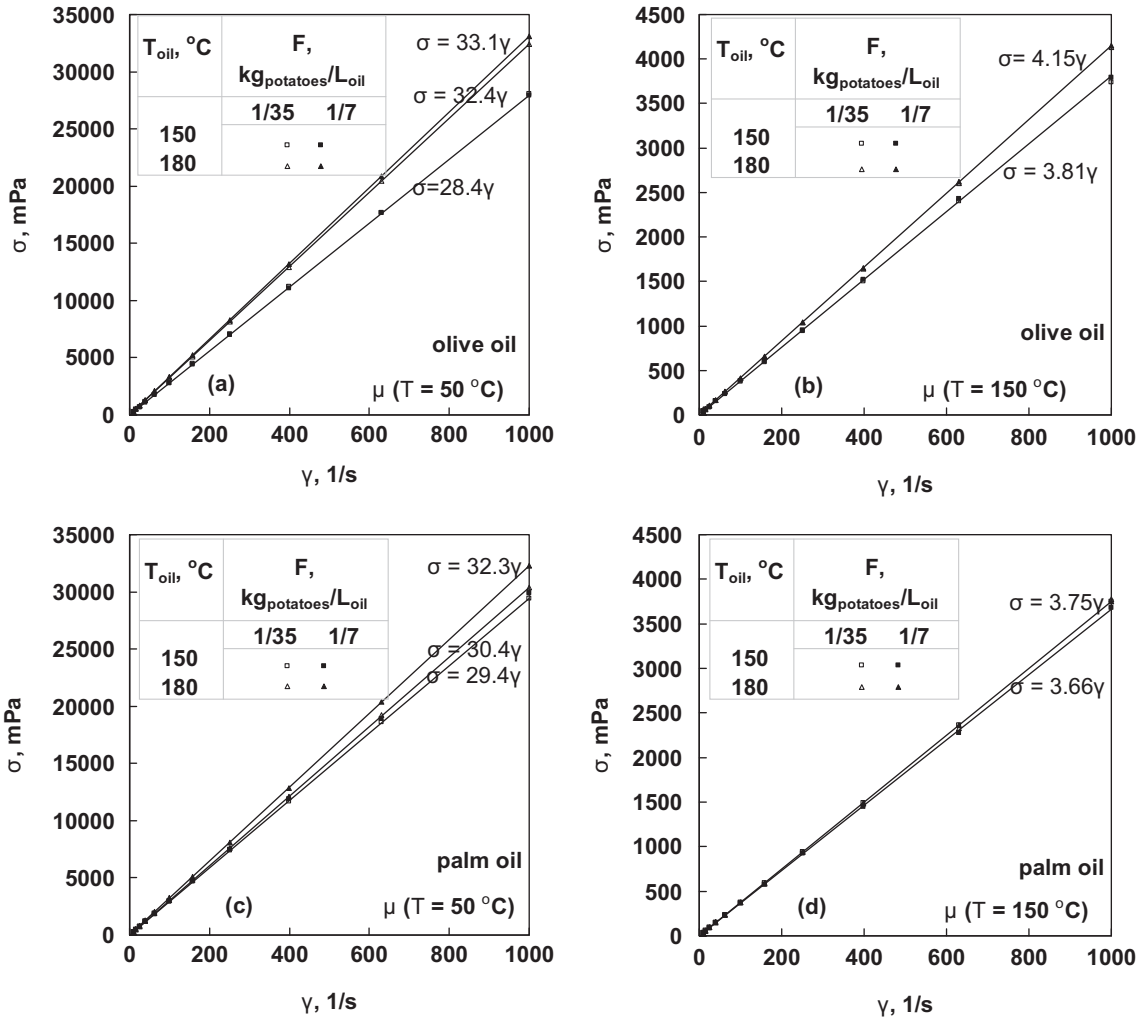

Fig. 2. Shear stress, σ, measurement at 50 °C and 150 °C for olive oil (a,b) and palm oil (c,d) as a function of shear rate, γ, conducted at high (1/7) and low (1/35) frying load ($kg_{potatoes}/L_{oil}$), at 150 and 180 °C initial frying temperatures for samples after the 40th frying batch.

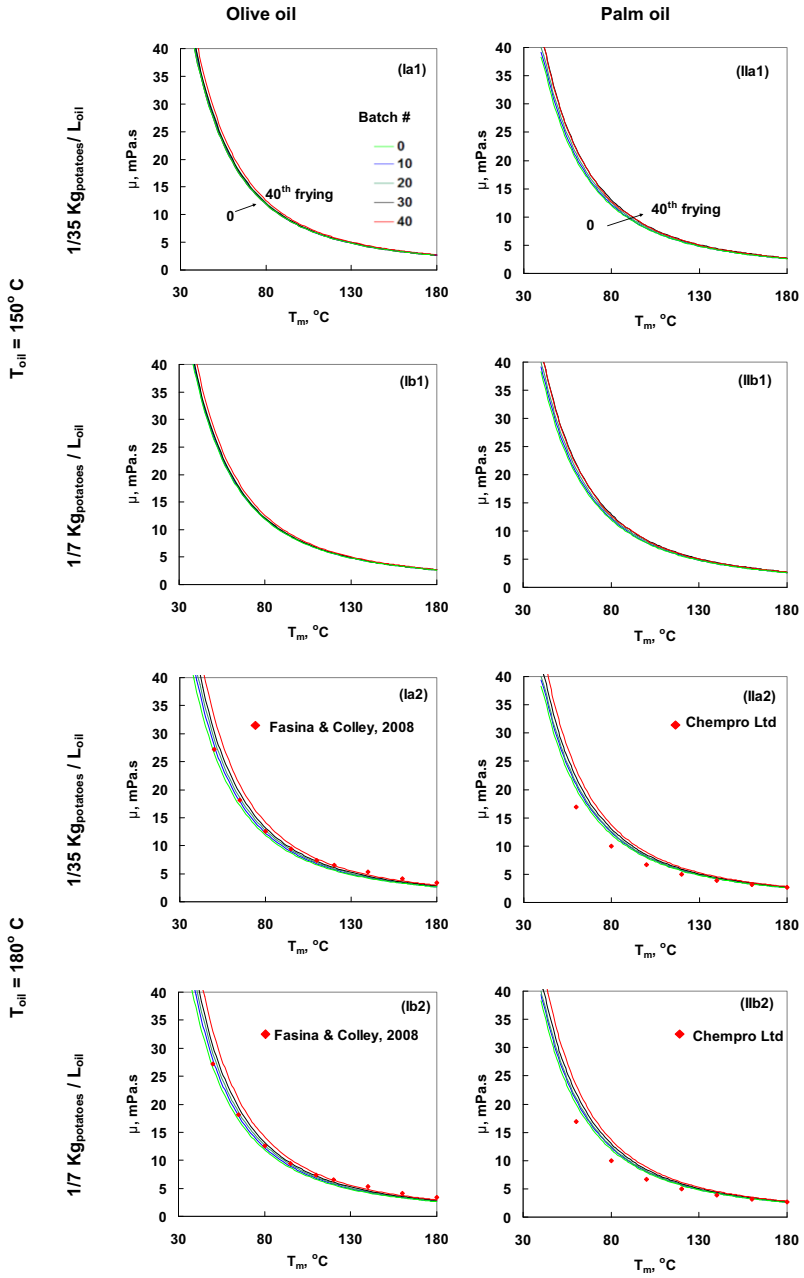

Fig. 3. Viscosity, μ, as a function of temperature. Results are for both olive (I) and palm oil (II) for frying loads 1/35 (a) and 1/7 $kg_{potatoes}/L_{oil}$ (b) initial frying temperatures 150 °C (1) and 180 °C (2) and for all the examined frying batches (10th, 20th, 30th, 40th) and fresh oil (0). (accuracy of viscosity measurements: ±0.1%, maximum deviation among replicates less than ±1.0% (average deviation ±0.75%).

and initial frying temperatures. It is seen that σ increases linearly with γ (starting from zero) which indicates that even the most degraded oil samples (viscosity is chiefly related to polymerization) exhibit virtually Newtonian behavior under the tested conditions. In other words, the viscosity is practically independent of the applied shear rate.

3.3. Viscosity measurements

Fig. 3 presents the dependence of viscosity on temperature for olive oil and palm oil for both examined frying loads and initial frying temperatures and along the forty sequential batches. The red dots in Fig. 3 stand for values from literature for fresh olive oil (Fasina and Colley, 2008) and palm oil (http://www.chempro.in/palmoilproperties.htm, 2011). As T_m (x axis) increases the viscosity of both oils decreases rapidly, as expected. Seemingly, the dependence of μ on T_m for fresh olive and palm oil agrees reasonably with earlier works in literature.

Due to poor scale resolution, Fig. 3 does not permit a clear differentiation and easy quantitative comparison between frying batches. For this reason, Fig. 4 plots the quantity $(\mu - \mu_0)/\mu_0 * 100$ versus the measurement temperature. Once more, μ represents the oil measured viscosity at a given temperature and given frying conditions whereas μ_0 stands for the viscosity of fresh palm or olive oil measured at the same temperature and frying conditions. It is apparent that the quantity $(\mu - \mu_0)/\mu_0 * 100$ varies appreciably with the measurement temperature. As T_m increases the deviation from the fresh oil values decreases. In general, this deviation increases as:

- The initial frying temperature, Tin, increases;
- The number of frying batches, F, increases.

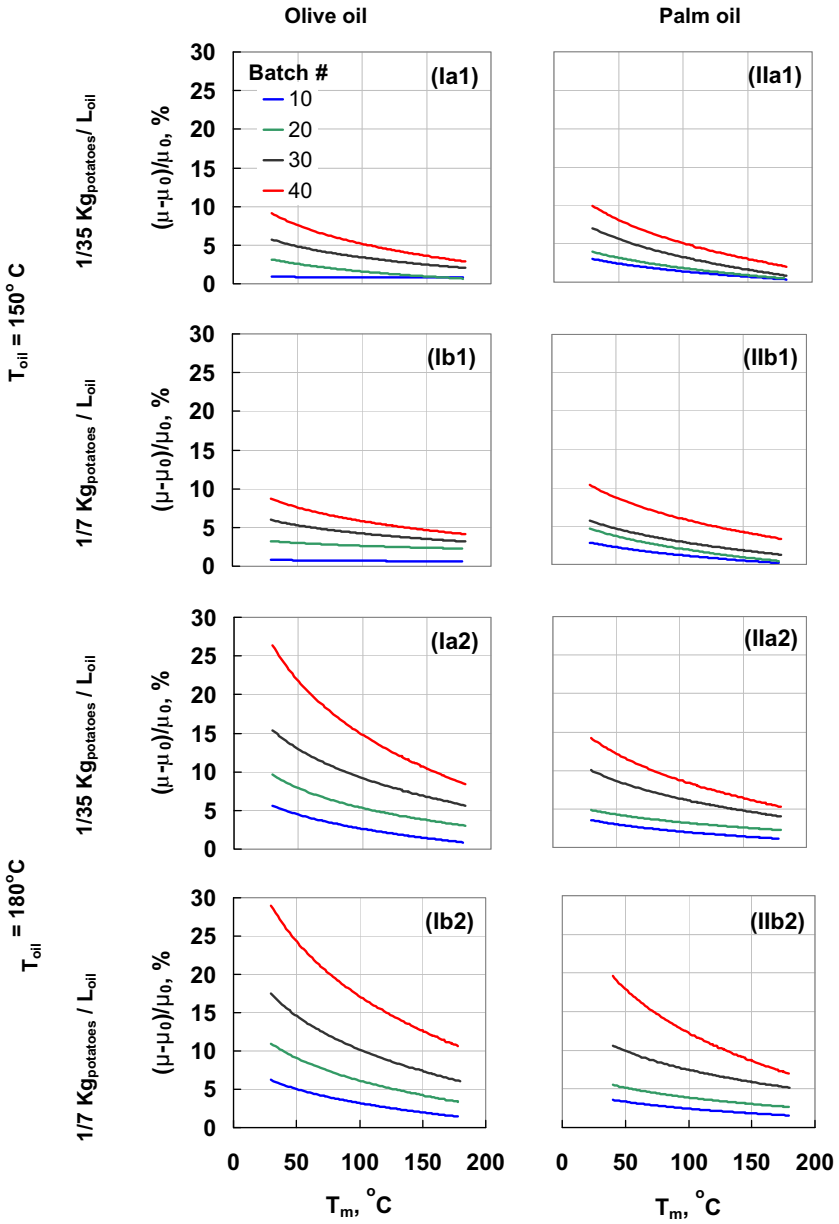

Fig. 4. Deviation% of the viscosity of fried oils from the viscosity of fresh oil, μ_0, versus temperature. Results are for both olive (I) and palm oil (II) for frying loads 1/35 (a) and 1/7 $kg_{potatoes}/L_{oil}$ (b) initial frying temperatures 150 (1) and 180 °C (2) and for all the examined frying batches (10th, 20th, 30th, 40th).

The $(\mu - \mu_0)/\mu_0 * 100$ values seem to be almost independent from the frying load but only for the lowest tested frying temperature (150 °C). Moreover, the palm oil viscosity is less affected by repeated frying than the viscosity of olive oil for the same frying conditions. For instance, after 40 frying batches at T_{in} = 180 °C, and F = 1/7/$Kg_{potatoes}/L_{oil}$, palm oil viscosity at 40 °C is ~20% higher than the fresh palm oil viscosity, while the olive oil viscosity is ~30% higher than the fresh olive oil viscosity.

4. Model development

In Table 1, one can see three expressions that have been chiefly used in literature to describe edible's oils dependence on temperature:

A. The Arrhenius equation:

$$\ln \mu = a + \frac{b}{T_m}, (T_m/K) \quad (2)$$

B. The Andrade–Arrhenius equation:

$$\ln \mu = a + \frac{b}{T_m} + \frac{c}{T_m^2}, (T_m/K) \quad (3)$$

C. The Williams – Lander – Ferry (WLF) equation:

$$\ln \mu = \frac{a + cT_m}{1 + bT_m}, (T_m/K) \quad (4)$$

where a, b and c are empirical parameters that are evaluated by fitting viscosity measurements with temperature. All three equations have been used to fit our data. The deviation between the measured and the predicted values for fresh and most degraded (40th frying batch, T_{in} = 180 °C, F = 1/7$kg_{potatoes}/L_{oil}$) olive and palm oil is presented in Fig. 5a–c parameters and the r^2 values are summarized in Table 3. It is seen that the predicted values by Eq.)((2)–

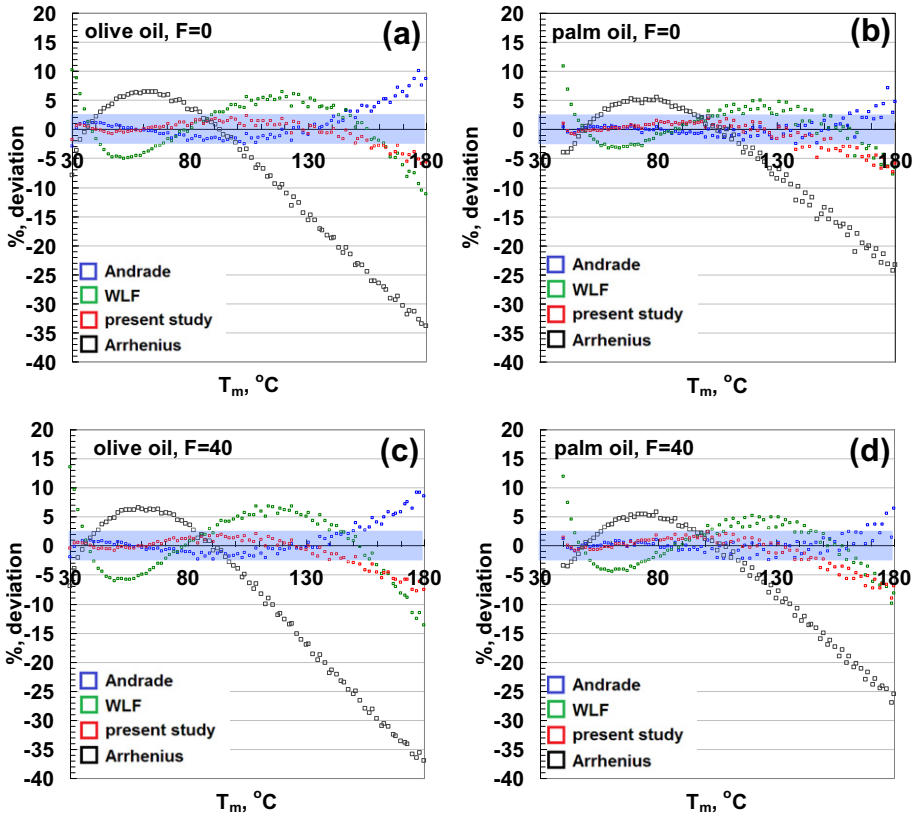

Fig. 5. Deviation% between the measured and the predicted values for olive oil (a,c) and palm oil (b,d) as a function of temperature, for fresh oils (a, b; $F = 0$) and for oils fried (c, d; $F = 40$) at high frying load (1/7 $kg_{potatoes}/L_{oil}$), at 180 °C initial frying temperature. F denotes the order of the frying batch. The horizontal blue stripe designates a zone with ±2.5% deviation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
a, b and c parameters and r^2 values as calculated after the fitting of Eqs. (2)–(5).

			Arrhenius: $ln\mu = a + \frac{b}{T_m}$	WLF: $\mu = \frac{a+cT_m}{1+bT_m}$	Arrhenius–Andrade: $ln\mu = a + \frac{b}{T_m} + \frac{c}{T_m^2}$	Present study: $ln\mu = a + b[ln(T_m - 273.15)]^2$
Olive oil	$F = 0$	a	−6.349	−7.505	2.319	6.382
		b	3127.04	−0.003477	−2778.64	−0.203
		c	–	0.0136	998310.7	–
		r^2	0.994	0.994	0.999	1.000
	$F = 40$	a	−6.658	−9.107	2.560	6.759
		b	3298.033	−0.003	−2957.072	−0.2133
		c	–	0.017	1053636.900	–
		r^2	0.994	0.991	0.998	1.000
Palm oil	$F = 0$	a	−5.865	−6.326	1.000	6.479
		b	2964.206	−0.003	−1868.656	−0.2075
		c	–	0.011	844416.580	–
		r^2	0.994	0.994	0.995	1.000
	$F = 40$	a	−6.110	−7.218	0.960	6.776
		b	3097.663	−0.003	−1865.245	−0.2160
		c	–	0.013	864959.114	–
		r^2	0.993	0.994	0.997	1.000

(Tm/K).

(4) deviate up to 35%, 10% and 10%, respectively, from the measured values. Aiming to find a simple equation that fits our data better than Eq. (2)–(4), we examined a library list of over 3,000 equations (TableCurve®). As can be seen in Fig. 5, Eq. (5) fits reasonably well our data ($r^2 = 1$).

$$\ln \mu = a + b[\ln(T_m - 273.15)]^2, \quad (T_m/K) \tag{5}$$

It must be noted that in the above models, described by Eqs. (2)–(5) absolute temperature values (K) are used to fit the data. Although for the highest temperatures (i.e.>∼150 °C), the deviation of Eq. (5) from measurements is comparable with that of the Arrhenius–Andrade and WLF model, Eq. (5) deviates less than ±2.5% (horizontal blue stripe) over the temperature range from 30 to 150 °C, where the WLF model appears unstable. Moreover, the model proposed in this study (Eq. (5)) is simpler than Andrade–Arrhenius and WLF models, since it involves only two fitting parameters.

Multiple quasi-linear regression analysis was employed to test if a and b parameters in Eqs. (2)–(5) depend on frying conditions. For this, a, b and c were calculated for 32 independent frying runs

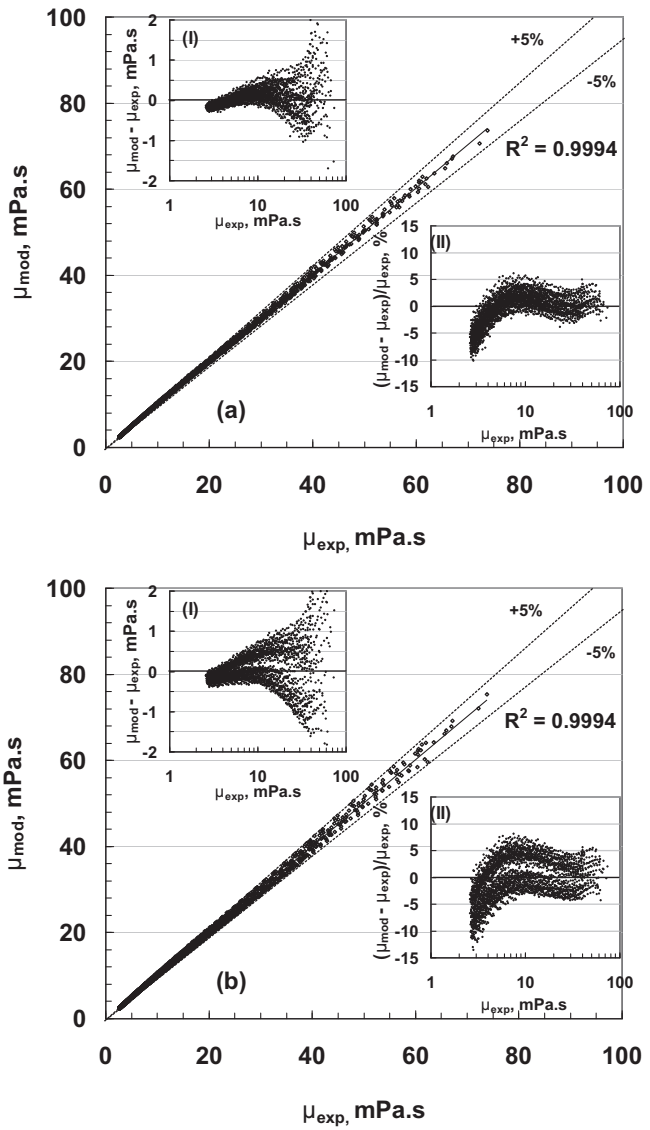

Fig. 6. Parity plot between the measured values and those predicted by the present model over all the examined frying conditions (oil types, frying loads, initial frying temperatures, frying batches). In (a) T_{ave} in the model is computed directly from experimental data; in (b) T_{ave} is estimated by Eq. (1). The small inset plots show the actual difference in viscosity values (top) and the% deviation (bottom) between the measured values and the model predictions.

(8 frying series × 4 frying batches i.e., 10th, 20th, 30th, 40th). Following the procedure described in a previous Section 2.3, it was found that only the parameters generated from fitting of experimental results with Eq 5 could be correlated with frying conditions at a satisfactory statistical level ($r^2 > 0.800$). In particular, a depends linearly on b and on the type of oil (Eq. (6)) while, in turn, b depends linearly on t_p, F, T_{ave} and on the type of oil (Eq. (7)).

$$a = -0.9213 + 35.99b - 0.07856^{*}TYPE, r^2 = 0.970 \quad (6)$$

$$b = 0.2029 - 8.2981 \times 10^{-5} t_p + 1.353 \times 10^{-4} F t_p + 6.4876 \times 10^{-7} T_{ave}{}^{*} t_p, r^2 = 0.900 \quad (7)$$

For the computation of Eqs 6 and 7 the experimental settings presented in Table 2 were taken into account. The estimated by the model Eqs (5)–(7) viscosity values, μ_{mod}, are plotted against the experimental ones, μ_{exp}, in a parity plot (Fig. 6). In Fig. 6*a*, T_{ave} values are those measured experimentally whereas in Fig. 6b T_{ave} values estimated by Eq. 1. It must be stressed that these T_{ave} values refer to the entire period t_p and so, in general, are different from the T_{ave} values computed from Eq. 1 which refer to single frying batches. It is seen that the proposed set of equations predicts the $\mu(T_m)$ profiles with an accuracy better than ±∼5% for most of the examined cases (bottom inset plots II in Fig. 6a and b). What is perhaps of greater significance is that for $T_m > 150$ °C which corresponds to usual frying processes and where viscosity takes values below 5 mPa.s, the deviation $\mu_{mod} - \mu_{exp}$ is less than ±0.2 mPa.s cases (top inset plots *II* in Fig. 6a and b).

5. Conclusions

Viscosity data acquired in a very dense temperature series give the opportunity to derive a two-parameters model equation that fits the $\mu(T_m)$ experimental data with greater accuracy ($r^2 = 1$) than other widely used equations (Arrhenius: $r^2 \sim 0.994$, WLF: $r^2 \sim 0.994$, Arrhenius–Andrade: $r^2 \sim 0.998$). The two parameters of the present model are linearly related to each other as well as to other frying parameters i.e., oil type, average oil temperature, frying load, frying time. For practical applications a linear expression is proposed for predicting the average oil temperature in a frying batch from the initial oil temperature, the specific heating power of the fryer and the initial mass of potatoes, $m_{potatoes}$ used in that frying batch. The derived model equations predict the experimental $\mu(T_m)$ profiles with reasonable accuracy (±∼5%).

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