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Mass, thermal and quality aspects of deep-fat frying of pork meat

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Abstract

Simultaneous heat and mass transfer and evolution of the physical properties of pork meat during deep-fat frying were studied. Frying was conducted at 90, 100 and 110 °C in sunflower oil and, only at 100 °C in shortening, just for comparison purpose. The moisture diffusivity coefficient exhibited values between 1.5 and 30.2×10^{-9} m^2/s, whereas the convective heat transfer coefficient ranged from 187.7 to 226.1 W/m^2 °C. Both transport phenomena were dependent of the frying temperature and there was not an effect of the nature of frying medium on the transport properties ($\alpha = 0.05$). Thermal diffusivity remained practically constant through the process; in contrast, the specific heat and thermal conductivity decreased with the increasing of frying time, due to moisture loss in the meat plates. Density, crust color and texture were affected by the frying temperature and frying medium type.

Keywords: Frying; Pork meat; Heat and mass transfer; Physical properties

1. Introduction

In Mexico, there are many food items prepared traditionally by immersion frying, and there is a lack of information about the process variables and product properties. "Carnitas" are a common food in the country, consisting in pork meat, marinated or not, deep-fat fried at relatively low temperature usually in pork shortening.

Shortenings have a distinctive natural flavor than is desirable for some foods, however, it is not a common ingredient because it limits the product stability (Matz, 1984).

In spite of frying is very used, researches about engineering aspects have been limited. Quantitative information to describe the heat rate, oil penetration into the food, oil degradation and crust development, and interactions between water and oil, among other aspects, is needed (Singh, 1995). Additionally, the snack foods, such as potatoes (chips and French fries) or tortilla chips, are the most studied fried products, but information about transport phenomena in fried meat products is scarce.

In the past decade, the heat or mass transfer during the frying of few meat products were attended overseas for some researchers. The deep-fat frying of beef meatballs at 159 ± 1 °C in beef shortening was modeled by Ateba and Mittal (1994), a complex solution was proposed by Rao and Delaney (1995) for heat transfer during the deep-fat frying of breaded chicken pieces, and Dincer and Yildiz (1996) proposed an unsteady state model for heat and mass transfer in sausages during frying.

Because frying of meat products should be analyzed to know its process particularities, the objective of this work was to study the evolution of the physical properties through deep-fat frying of pork meat plates and to obtain the parameters of the simultaneous heat and

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Nomenclature

A	surface area (m^2)
a	Redness Hunter parameter (dimensionless) for pork meat at t
a_0	Redness Hunter parameter (dimensionless) for raw pork meat, $t = 0$
b	Hunter parameter (dimensionless) for pork meat at t
b_0	Hunter parameter (dimensionless) for raw pork meat, $t = 0$
c	concentration of liquid in any point in the sample (%) in Eq. (3)
C_p	specific heat (kJ/kg °C)
D	moisture diffusivity coefficient (m^2/s)
d	the half of thickness plate (m)
F_p	penetration force (N)
h	heat transfer coefficient (W/m^2 °C)
k	thermal conductivity (W/m °C)
L	luminosity Hunter parameter (dimensionless) for pork meat at t
L_0	luminosity Hunter parameter (dimensionless) for raw pork meat, $t = 0$
m	meat plate mass (kg)
n	number of terms in the series in Eq. (4)
Q	heat flow rate (J/s)
t	frying time (s)
T_0	initial meat temperature (°C)
T_b	temperature of the bulk fluid (°C) in Eq. (6)
T_e	temperature of the external fluid (oil/fat) at equilibrium (°C)
T_s	average surface temperature (°C) in Eq. (6)
V	meat plate volume (m^3)
W	moisture content of pork meat (% dry basis) at t
W_0	initial moisture content of raw pork meat (% dry basis), $t = 0$
W_m	moisture content in the meat surface immersed in frying medium (supposed 0 by assuming negligible surface resistance)
x	position in the sample (m), where the concentration is W
Y	unaccomplished moisture concentration change (dimensionless)

Greek symbols

α	thermal diffusivity (m^2/s)
ΔE	net difference color (dimensionless)
ΔT	temperature gradient (°C)
ΔX	thickness of the meat plate $= 2d$ (m)
ΔY	wideness of the meat plate $= 2e$ (m)
ΔZ	largeness of the meat plate $= 2f$ (m)
ρ	density (kg/m^3)

mass transfer during the process, considering the effect of frying temperature and type of the frying medium.

2. Experimental

2.1. Frying experiments

Lean pork meat was obtained from leg muscle from a local supermarket. Frozen meat was cut in plates of $5 \times 4 \times 2$ cm and covered with plastic film to avoid surface dehydration until experimentation. Frying was conducted during 2 h taking samples each 30 min for different analyses. Two frying media were employed: sunflower oil (an unsaturated fat), at 90, 100 and 110 °C, and shortening (a saturated fat) at 100 °C. These frying temperatures were selected, because they are the used conditions in Mexico for cooking preparation of the pork meat known as "Carnitas". Shortening was included in the experiments to observe the effect of frying medium in the process (fat absorption, heat transfer, physical properties), however, frying with shortening was carried out only at 100 °C, a representative temperature of the process. Comparisons respect to the frying medium will be done at this temperature.

2.2. Moisture and fat contents

The moisture content was determined by method 7.003 (AOAC, 1995), whereas the fat content, was quantified by extraction with petroleum ether during 6 h in a Goldfisch equipment.

2.3. Temperature measurement

The center temperature profile for meat pieces through frying process was obtained with a thermocouple type J inserted into the center plate. The thermocouple was connected to a digital thermometer (Cole Parmer, Barrington, NY).

2.4. Thermo-physical properties determination

Raw and fried meat thermal properties were evaluated with a Thermolink instrument (Thermal Properties Meter for Food-2.5, Decagon Devices, Pullman, WA). This is a nanovoltmeter with a sensor probe consisting of a heater and a chromel–constantan thermocouple; when the differences between temperatures are minimized, 60 s are required to display the measurements. Thermal properties (specific heat, thermal conductivity and thermal diffusivity) were determined inserting the instrument's probe in the center of the meat plate, and the obtained values were a mass average.

Density was calculated from the relation

$$\rho = \frac{m}{V} \tag{1}$$

V was calculated by the product of the large, width and thickness of the raw and fried meat plates, thus this property is a meat overall density, being the same for crust and core.

2.5. Quality attributes

External color of raw and fried meat pork was measured by reflectance mode in a Color Gard System colorimeter (Hunter Lab., Reston, VA), using the Hunter parameters L, a and b. The instrument was calibrated using the black tile and the white standard ($L = 92.89$, $a = -1.05$, $b = 0.82$).

Additionally, the net color difference was calculated with the relation

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2} \tag{2}$$

Texture is a predominant component in meat quality (Dransfield, Francombe, & Whelehan, 1984). Particularly, in fried products, the crust developing is a textural parameter highly appreciated by consumers. Fried meat texture was measured by a puncture test on the crust, at 5 mm/s using a 1/8 in spindle, penetrating 15% of the thickness by using a Texture Analyzer TA.TX2 (Texture Technologies, Corp., Scardale, NY) and the Texture Expert software (version 1.22, 1999). The peak in the curve was considered as the penetration force.

2.6. Statistical analysis

All analyses were carried out in triplicate. ANOVA and Tukey's pairwise comparisons were carried out for data analysis using statistical software (Minitab Release 14, Minitab Inc., State College PA).

3. Analysis

3.1. Mass transfer

For moisture loss in the pork meat plates, diffusion was assumed as the predominant phenomenon for the mass transfer, considering than the steam migrates principally through the whole plate. This moisture transfer phenomenon has been modeled in one dimension, in which the concentration can be described by the Fick's second law of diffusion (Rice & Gamble, 1989)

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \tag{3}$$

where the Newman's solution to Eq. (3) for an infinite slab (Rice & Gamble, 1989; Welty, Wilson, & Wicks, 1976) is given by

$$\frac{W - W_m}{W_0 - W_m} = \frac{8}{\pi^2} \times \sum_{n=0}^{\infty} \left\{ \frac{1}{(2n+1)^2} \times \left[\exp\left(-\frac{(2n+1)^2 \pi^2 D t}{4d^2} \right) \right] \right\} = Y_{\Delta X} \tag{4}$$

and similarly, for two (rectangular plate with sealed ends) and three dimensions (finite or rectangular plate) (Welty et al., 1976)

$$\frac{W - W_m}{W_0 - W_m} = Y_{\Delta X} \cdot Y_{\Delta Y} \tag{5}$$

$$\frac{W - W_m}{W_0 - W_m} = Y_{\Delta X} \cdot Y_{\Delta Y} \cdot Y_{\Delta Z} \tag{6}$$

where the shrinkage of the product was supposed as negligible. Given than the sample of pork meat employed in this study corresponds to a finite body, the solution involves the product of two infinite slabs.

3.2. Heat transfer

The chosen model to describe the heat transfer during pork meat frying (lumped parameter analysis) was selected by its simplicity over other models, such as finite difference or finite element. This simple approach has been used with the same objectives in other frying studies, in which the convection mechanism is controlling the heat transfer, such as the tortilla chips frying (Moreira, Palau, & Sun, 1995).

The heat transfer can be expressed by Newton's law of cooling

$$Q = hA\Delta T \tag{7}$$

The heat transfer coefficient is not a food property, but is one of the important parameters necessary to design and control food processing where fluids are subjected to heating, cooling or frying medium (Rahman, 1995). Thus, h was calculated for the deep-fat frying of pork meat, considering a quasi-steady state, given when the temperature inside the solid is uniform and the heat balance can be described as

$$hA(T_s - T_b) = \rho V C_p \frac{\partial T}{\partial t} \tag{8}$$

The last differential equation, solved with the proper initial condition, is expressed as

$$\frac{T_s - T_e}{T_0 - T_e} = \exp\left(\frac{-hA}{\rho V C_p} t \right) \tag{9}$$

For this case, the solid was the pork meat plate and the fluid the frying medium.

4. Results and discussion

4.1. Mass transfer

Initial moisture content of pork meat was quantified between 72.4% and 75.95% (wet basis). Fig. 1 shows the moisture loss during the frying of meat plates at different temperatures. Similar trends were observed during frying at 90 and 100 °C, without a noticeable effect of the frying medium ($\alpha = 0.05$). Bigger moisture loss occurred when the frying process was carried out at 110 °C.

The rapid decreasing in moisture loss in the first minutes of frying, reported for other meat products, such as chicken nuggets (Balasubramaniam, Mallikarjunan, & Chinnan, 1995) and chicken strips (Vélez-Ruiz, Vergara-Balderas, Sosa-Morales, & Xique-Hernández, 2002), was not observed in this study, except when the frying temperature was 110 °C.

Moisture diffusivity coefficient was obtained from Eq. (5), for $n = 1$ at each studied temperature, and considering that the largeness was not important in the diffusion (based on moisture results and fitting calculations). The calculated values are shown in Table 1, which ranged from 1.59 to 30.20×10^{-9} m^2/s. These values are similar than those reported by Ateba and Mittal (1994) for frying of meatballs (2.87×10^{-8} m^2/s), and by Moreira et al. (1995) for frying of tortilla chips (9.34×10^{-8} m^2/s), and lower than the reported by Dincer and Yildiz (1996) for frying of sausages at 180 °C (1.31×10^{-7} m^2/s), but bigger than some values cited by Rice and Gamble (1989) for potato slices fried at 145 °C (14 and 24×10^{-10} m^2/s for the first 30 and 60 s, respectively). Then, the differences may be attributed to the food nature and particular process performance (temperature and time).

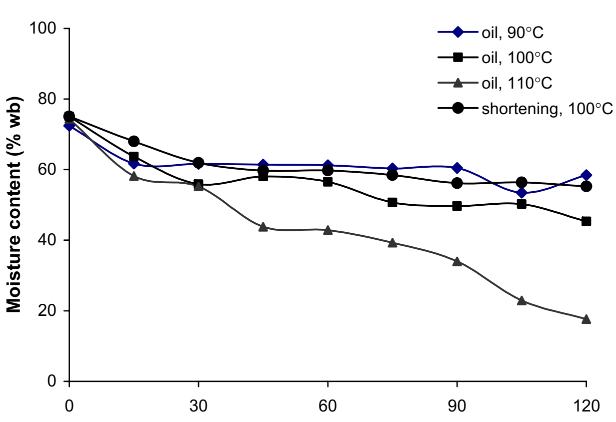

Fig. 1. Moisture loss during the deep-fat frying of pork meat plates at different temperatures in sunflower oil and shortening.

In the deep-fat frying of pork meat, similar moisture loss occurred when the food was fried at 90 °C in sunflower oil and in shortening at 100 °C, and the biggest loss was observed in the frying with sunflower oil at 110 °C, as can be seen in Table 1, and there was not a significant effect of the frying medium (oil and shortening at 100 °C) on the moisture evaporation from the pork meat during the process ($\alpha = 0.05$).

The initial fat content in the meat was 1.3–1.7% (wet basis), being very low due to the employed lean muscle. Fat uptake through pork meat frying is presented in Fig. 2. As expected, fat content increased with frying time for any medium and temperature. In the studied period of time, a linear relationship among gained fat versus process time was observed. The computed empirical relationships for this linear response in the fat increasing were

Frying in sunflower oil at 90 °C

$$\%\text{Fat} = 0.092t + 1.827, \quad R^2 = 0.941 \tag{10}$$

Frying in sunflower oil at 100 °C

$$\%\text{Fat} = 0.081t + 0.878, \quad R^2 = 0.942 \tag{11}$$

Frying in sunflower oil at 110 °C

$$\%\text{Fat} = 0.120t + 1.472, \quad R^2 = 0.942 \tag{12}$$

Frying in shortening at 100 °C

$$\%\text{Fat} = 0.056t + 1.146, \quad R^2 = 0.999 \tag{13}$$

Table 1
Transport phenomena parameters in the deep-fat frying of pork meat plates in two frying media at different temperatures

Frying medium	T (°C)	$D \times 10^9$ (m^2/s)	h (W/m^2 °C)
Sunflower oil	90	1.59 ± 0.14^a	174.38 ± 18.57^a
	100	9.15 ± 0.49^b	193.45 ± 10.87^{ab}
	110	30.20 ± 0.75^c	226.10 ± 14.29^b
Shortening	100	3.56 ± 0.55^a	200.60 ± 17.18^{ab}

Determinations were done by triplicate. Means with the same letter are not significantly different respect to T ($\alpha = 0.05$). T = frying temperature.
D = moisture diffusivity coefficient, h = convective heat transfer coefficient.

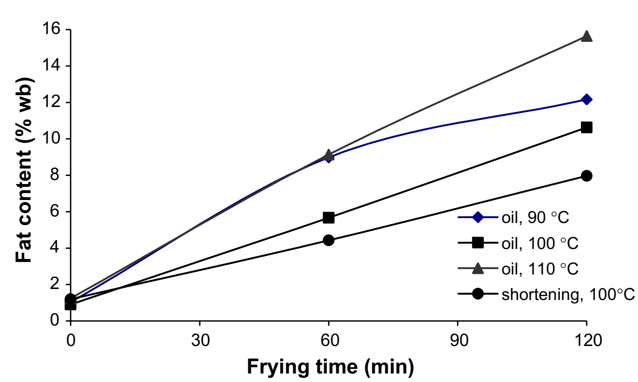

Fig. 2. Fat uptake during the deep-fat frying of pork meat plates at different temperatures in sunflower oil and shortening.

Some authors have reported an increasing in oil content when the oil temperature was increased, such as Gamble, Rice, and Selman (1987) for potato slices, Moreira et al. (1995) for tortilla chips and Vélez-Ruiz et al. (2002) for chicken strips, but in the deep-fat frying of pork meat plates the increasing of fat content did not follow a direct relation respect to frying temperature. However, the frying medium type significantly affected the fat uptake ($\alpha = 0.05$), occurring a lower fat absorption when shortening was used in the process. This event could be explained by taking account of the replacement of water for fat uptake through the frying and the fat/oil molecule size. Saturated fat is formed by molecules with bigger size than non-saturated oils, limiting or avoiding the entrance to the small pores previously generated by the water vapor when it was removed during frying.

4.2. Thermo-physical properties results

The results of raw and fried pork meat thermal properties from Thermolink are shown in Table 2. C_p and k decreased with the increasing of frying time, due to moisture loss, while α was practically constant through the process. k and C_p were significantly affected by the frying temperature ($\alpha = 0.05$).

The values of pork meat thermal properties were similar to those reported for other meat products. For specific heat, Chen (1990) found a $C_p = 3.77$ kJ/kg °C for beef, Rahman (1995) published a $C_p = 3.054$ kJ/kg °C for lean pork with a water fraction of 0.57 and a $C_p = 3.431$ kJ/kg °C for lean beef with a water fraction of 0.72; in this study, the C_p of fried pork meat ranged between 2.77 and 4.43 kJ/kg °C as a function of frying temperature. The reported thermal conductivity for beef was 0.368 and 0.598 W/m °C for water fractions of 0.578 and 0.613, respectively (Baghe-khandan, Okos, & Sweat, 1982) which are in the range of the values experimentally determined in this work for the pork meat plates (0.35–0.66 W/m °C, as a function of the frying time and temperature).

In the case of thermal diffusivity, Singh (1982) determined this property for chuck, round and tongue of beef with values from 1.23 to 1.33×10^{-7} m^2/s, Poulsen (1982) cited an $\alpha = 1.46 \times 10^{-7}$ m^2/s for fresh meat, Ateba and Mittal (1994) reported $\alpha = 1.33 \times 10^{-7}$ m^2/s for fried meatballs at 160 °C, and Dincer and Yildiz (1996) calculated $\alpha = 3.846 \times 10^{-7}$ m^2/s in sausages during frying at 180 °C. The cited values are in agreement with those determined in this research being from 1.12 to 1.83×10^{-7} m^2/s for different frying times and temperatures.

Density values of fresh pork meat ranged between 1082.3 and 1099.7 kg/m^3, being very similar to those reported by Sanz, Alonso, and Mascheroni (1987) for pork boneless (1090 kg/m^3) and for ham (1070 kg/m^3). Some relevant observations for the changes of the pork meat density through of frying process were detected in this study (Table 2). Frying medium did not affect the density, while than the frying temperature affected significantly ($\alpha = 0.05$), density was lower when the frying

Table 2
Thermo-physical properties of pork meat plates during deep-fat frying in two frying media at different temperatures

Frying medium	T (°C)	t (min)	C_p (kJ/kg °C)	k (W/m °C)	$\alpha \times 10^7$ (m^2/s)	ρ (kg/m^3)
Sunflower oil	90	0	4.54 ± 0.23	0.79 ± 0.05	1.83 ± 0.04	1090.0 ± 11.8
		30	3.56 ± 0.61	0.66 ± 0.04	1.67 ± 0.09	1079.7 ± 11.6
		60	3.54 ± 0.28	0.60 ± 0.06	1.41 ± 0.36	1071.3 ± 3.1
		90	3.36 ± 0.15	0.59 ± 0.04	1.35 ± 0.24	1049.7 ± 7.6
		120	3.13 ± 0.11	0.59 ± 0.05	1.67 ± 0.16	1038.3 ± 4.2
	100	0	3.99 ± 0.40	0.65 ± 0.04	1.48 ± 0.07	1099.7 ± 20.8
		30	3.78 ± 0.21	0.61 ± 0.02	1.50 ± 0.06	1077.0 ± 34.0
		60	3.35 ± 0.21	0.59 ± 0.02	1.64 ± 0.25	1073.3 ± 39.3
		90	3.31 ± 0.28	0.57 ± 0.02	1.76 ± 0.06	1043.7 ± 8.0
		120	2.78 ± 0.11	0.56 ± 0.01	1.65 ± 0.01	1023.7 ± 10.8
	110	0	3.72 ± 0.19	0.68 ± 0.00	1.54 ± 0.10	1082.3 ± 8.4
		30	3.58 ± 0.23	0.64 ± 0.01	1.69 ± 0.17	1065.3 ± 14.4
		60	3.17 ± 0.02	0.56 ± 0.04	1.83 ± 0.07	1057.3 ± 17.1
		90	2.85 ± 0.08	0.51 ± 0.02	1.65 ± 0.05	1025.3 ± 20.0
		120	2.77 ± 0.04	0.35 ± 0.00	1.63 ± 0.25	996.0 ± 14.1
Shortening	100	0	4.62 ± 0.20	0.62 ± 0.04	1.63 ± 0.20	1090.3 ± 11.6
		30	4.43 ± 0.16	0.60 ± 0.06	1.45 ± 0.22	1051.7 ± 32.8
		60	3.76 ± 0.19	0.56 ± 0.04	1.12 ± 0.11	1042.0 ± 13.0
		90	3.46 ± 0.18	0.55 ± 0.04	1.41 ± 0.02	1036.3 ± 16.4
		120	3.41 ± 0.27	0.53 ± 0.03	1.15 ± 0.11	1030.7 ± 10.6

Determinations were done by triplicate. T = frying temperature, t = frying time, C_p = specific heat, k = thermal conductivity, α = thermal diffusivity, ρ = density.

temperature increased. For frying at temperature of 90 and 110 °C, there was an effect of the frying time on this property: density diminished with the increasing of frying time, result attributed to the water loss and oil uptake; but when the temperature was 100 °C, for both employed media (oil and shortening), the frying time did not affect the fried pork meat density ($\alpha = 0.05$). A constant density was observed at 100 °C, without significant difference through process time and without influence of the frying medium saturation ($\alpha = 0.05$).

4.3. Heat transfer

Inner temperature in the meat plate increased quickly when it was introduced in the fryer. Around 20 min of processing were required for the inner temperature to reach the oil/fat frying temperature for all studied frying temperatures, and maintained up to the end of the frying (Fig. 3). For every frying time, the meat temperature was bigger while the process temperature augmented.

From Eq. (9), the heat transfer coefficient was calculated by solving with the different frying conditions (Table 1). An increasing of h was observed when the frying temperature increased, and there was not a significant effect of type of frying medium in this transfer parameter ($\alpha = 0.05$). The obtained values (174.38–226.10 W/m^2 °C) were similar than those reported by Califano and Calvelo (1991), who found values of h between 150 and 165 W/m^2 °C in the frying process of potato, when the temperature was 50–100 °C; Miller, Singh, and Farkas (1994) obtained h that ranged from

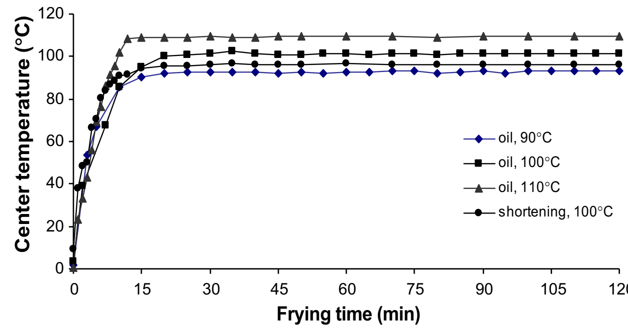

Fig. 3. Experimental temperature profiles during the deep-fat frying of pork meat plates at different temperatures in sunflower oil and shortening.

247.8 to 276.2 W/m^2 °C, under non-boiling conditions and employing different oils; most recently, Vélez-Ruiz et al. (2002), published data of $h = 207.6$ W/m^2 °C at 130 °C; $h = 223.3$ W/m^2 °C at 140 °C and $h = 331.0$ W/m^2 °C at 150 °C for the frying of chicken plates in sunflower oil.

These results indicate than the assumption of uniform inside solid temperature can be taken to solve the Eq. (8), because the computed values are in agreement with those reported in the literature.

4.4. Quality attributes

Color of raw pork meat corresponded to pale red and exudative, which was observed in a and L values (Table 3). Varnan and Sutherland (1995) reported than the

Table 3
Hunter parameters for crust color of pork meat plates during deep-fat frying in two frying media at different temperatures

Frying medium	T (°C)	t (min)	L	a	b
Sunflower oil	90	0	40.07 ± 4.94	8.20 ± 2.61	3.21 ± 0.89
		30	34.71 ± 3.61	4.62 ± 1.74	10.53 ± 2.49
		60	32.12 ± 5.69	4.16 ± 1.75	10.23 ± 2.71
		90	30.91 ± 3.80	5.26 ± 1.87	10.03 ± 3.57
		120	28.77 ± 1.61	5.27 ± 2.23	10.01 ± 3.95
	100	0	38.55 ± 5.77	6.27 ± 0.81	2.50 ± 0.16
		30	33.10 ± 4.18	4.74 ± 0.54	6.96 ± 2.20
		60	28.16 ± 1.98	4.37 ± 0.08	8.85 ± 1.28
		90	27.58 ± 2.70	4.65 ± 0.99	7.26 ± 1.95
		120	23.24 ± 1.83	3.52 ± 0.03	4.76 ± 0.90
	110	0	37.59 ± 5.68	7.43 ± 2.47	3.38 ± 0.95
		30	30.98 ± 3.29	4.44 ± 1.51	8.67 ± 3.04
		60	29.63 ± 4.60	5.30 ± 1.23	8.43 ± 2.38
		90	25.89 ± 3.13	5.09 ± 0.76	8.38 ± 1.33
		120	21.61 ± 1.70	5.51 ± 0.74	8.12 ± 1.32
Shortening	100	0	37.97 ± 2.76	5.71 ± 0.41	3.43 ± 0.17
		30	32.05 ± 2.56	3.20 ± 0.19	5.87 ± 0.15
		60	30.97 ± 1.34	2.85 ± 0.33	6.25 ± 0.60
		90	29.34 ± 0.59	2.34 ± 0.23	6.87 ± 0.69
		120	27.30 ± 1.02	2.48 ± 0.39	6.00 ± 0.07

Determinations were done by triplicate. T = frying temperature, t = frying time, L = luminosity, a = green–red, b = blue–yellow.

coloration is the result of the presence of the fresh meat pigments such as myoglobin, oxymyoglobin (the oxygenated form of myoglobin, with Fe^{2+}) and in lower quantity the metmyoglobin (it has iron in the oxidized state, Fe^{3+} and H_2O at the sixth coordination point).

Hunter parameters for crust color of fried pork meat were affected by frying process time: *L* diminished, while *a* and *b* augmented through the process (Table 3), but there was not an effect of the frying temperature ($\alpha = 0.05$). Pork meat appearance was developing brown color when the frying time increased. Changes in color of meat pork during the deep-fat frying is due to cooking process than involve some chemical reactions such as oxidation of the iron to Fe^{3+}, responsible of brown color and myoglobin denaturation. In general terms, the cooked meat color is determined by the globin haemochromogen formation and the quantity of undenatured myoglobin (including oxymyoglobin) present (Varnan & Sutherland, 1995). Oxidation and polymerization of fats, and other pathways implicating protein and carbohydrates participate in the final color of the cooked meat (Bodwell & McClain, 1976).

The decreasing in luminosity during the deep-fat frying is a typical change and it has been reported for other fried products such as potatoes (Krokida, Oreopoulou, Maroulis, & Marinos-Kouris, 2001) and donuts (Vélez-Ruiz & Sosa-Morales, 2003).

Fig. 4 shows the color changes (net color difference) in the pork meat during the frying process at the studied temperatures. As it was expected, and as a well recognized characteristic of fried products, the color changes increased with the advance of frying time; similar trend was reported for Moyano, Ríoseco, and González (2002) for the crust color changes during the frying of impregnated potato strips. For frying in sunflower oil, color was affected by frying temperature and the change was bigger at higher temperature. A significant effect of frying medium was observed on the crust color changes ($\alpha = 0.05$), being lowest when shortening was utilized.

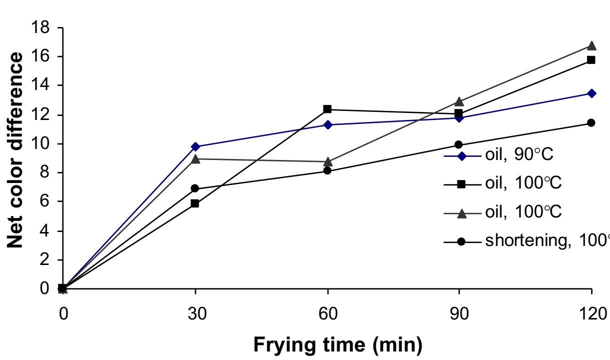

Fig. 4. Evolution of the net color difference during the deep-fat frying of pork meat plates at different temperatures in sunflower oil and shortening.

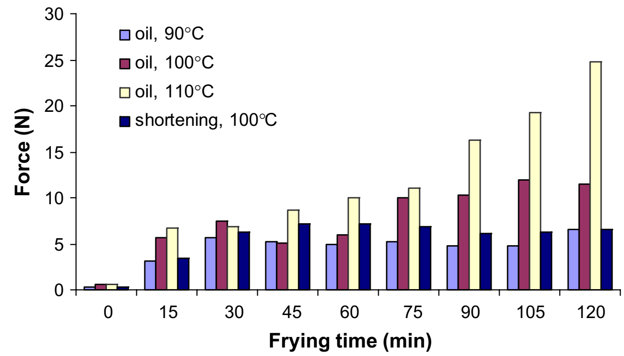

Fig. 5. Variation of the penetration force (15%) in the crust of fried pork meat plates at different temperatures in sunflower oil and shortening.

Respect to texture, the penetration force on the fried meat crust increased with the frying time and process temperature (Fig. 5), indicating than the crust was harder when the process advanced, as a typical characteristic of frying foods. Also, increasing in the force is a consequence of the meat global cooking. Bigger hardness was observed when the frying temperature was elevated in the experiments with sunflower oil. Similar relation between texture and temperature was reported in cooked beef, where the increasing in cooking temperature produced an overall increase in shear and compression parameters (Mathevon, Mioche, Brown, & Culioli, 1995). In this study, the nature of frying medium had an effect on the developed texture ($\alpha = 0.05$), the fried meat in shortening showed lower force penetration through the whole frying process in comparison with the fried meat plates in sunflower oil at the same frying temperature (100 °C).

5. Conclusion

For deep-fat frying of pork meat, diffusion was assumed as the principal mechanism of moisture loss and a simple solution was employed for heat transfer in a quasi-steady state. The transport parameters, *D* for mass transfer and *h* for heat transfer, were affected by the temperature of the process, and exhibited similar values to other frying processes of foods. Frying medium type did not affect these transport phenomena ($\alpha = 0.05$).

The thermo-physical properties and the quality attributes were affected by frying time and temperature, with exception of thermal diffusivity than remained constant through the process and without effect of process temperature, while density was not affected by the frying time when the experiments were conducted at 100 °C in both frying media.

The frying in shortening is the accustomed pathway of production of fried pork meat (“carnitas”) in Mexico.

The frying in saturated fat resulted comparable and statistically non-different respect to the frying in oil, and in some cases such as the lower final fat content, better color and soft texture, have showed certain advantages.

References

AOAC (1995). *Official methods of analysis*. Washington, DC: Association of Official Analytical Chemists.

Ateba, P., & Mittal, G. S. (1994). Modelling the deep-fat frying of beef meatballs. *International Journal of Food Science and Technology, 29*, 429–440.

Balasubramaniam, V. M., Mallikarjunan, P., & Chinnan, M. S. (1995). Heat and mass transfer during deep-fat frying of chicken nuggets coated with edible film: influence of initial fat content. *CoFE*, 103–106.

Baghe-khandan, M. S., Okos, M. R., & Sweat, V. E. (1982). The thermal conductivity of beef as affected by temperature and composition. *Transactions of the ASAE, 25*, 1118.

Bodwell, C. E., & McClain, P. E. (1976). Composición química de los tejidos animales. Proteínas. In J. F. Price & B. S. Schweigert (Eds.), *Ciencia de la carne y de los productos cárnicos* (pp. 102). Acribia: Zaragoza, España.

Califano, A. N., & Calvelo, A. (1991). Thermal conductivity of potato between 50 and 100 °C. *Journal of Food Science, 56*, 586–589.

Chen, C. (1990). Factors influencing mutagen formation during frying of ground beef. *Dissertation Abstracts International, 49*(9), 3524, FSTA, (1): S0030. Cited by Boskou D. & Elmadfa I. (1999). *Frying of food: Oxidation, nutrient and non-nutrient antioxidants, biologically active compounds and high temperatures*. Technomic Publishing Co. Inc. 89.

Dincer, I., & Yildiz, M. (1996). Modelling of thermal and moisture diffusions in cylindrically shaped sausages during frying. *Journal of Food Engineering, 28*, 35–43.

Dransfield, E., Francombe, M. A., & Whelehan, O. P. (1984). Relationships between sensory attributes in cooked meat. *Journal of Texture Studies, 15*, 33–48.

Gamble, M. H., Rice, P., & Selman, J. D. (1987). Relationship between oil uptake and moisture loss during frying of potato slices from c.v. Record UK tubers. *International Journal of Food Science and Technology, 22*, 233–241.

Krokida, M. K., Oreopoulou, V., Maroulis, Z. B., & Marinos-Kouris, D. (2001). Colour changes during deep-fat frying. *Journal of Food Engineering, 48*, 219–225.

Mathevon, E., Mioche, L., Brown, W. E., & Culioli, J. (1995). Texture analysis of beef cooked at various temperatures by mechanical measurements sensory assessments and electromyography. *Journal of Texture Studies, 26*, 175–192.

Matz, S. A. (1984). *Snack food technology* ((2nd ed., p. 29) 19). Westport: The AVI Publishing Company.

Miller, K. S., Singh, R. P., & Farkas, B. E. (1994). Viscosity and heat transfer coefficients for canola, corn, palm and soybean oil. *Journal of Food Processing and Preservation, 18*, 461–472.

Moreira, R. G., Palau, J., & Sun, X. (1995). Simultaneous heat and mass transfer during deep fat frying of tortilla chips. *Journal of Food Process Engineering, 18*, 307–320.

Moyano, P. C., Ríoseco, V. K., & González, P. A. (2002). Kinetics of crust color changes during deep-fat frying of impregnated french fries. *Journal of Food Engineering, 54*, 249–255.

Poulsen, K. P. (1982). Thermal diffusivity of foods measured by simple equipment. *Journal of Food Engineering, 34*(1), 115.

Rahman, S. (1995). *Food properties handbook* ((p. 394) 239). Boca Ratón, FL: CRC Press.

Rao, V. N. M., & Delaney, R. A. M. (1995). An engineering perspective on deep-fat frying of breaded chicken pieces. *Food Technology, 49*(4), 138–141.

Rice, P., & Gamble, M. H. (1989). Technical note: Modeling moisture loss during potato slice frying. *International Journal of Food Science and Technology, 24*, 183–187.

Sanz, P. D., Alonso, M. D., & Mascheroni, R. H. (1987). Thermophysical properties of meat products: General bibliography and experimental values. *Transactions of the ASAE, 30*, 283.

Singh, R. P. (1982). Thermal diffusivity in food processing. *Food Technology, 36*(2), 90.

Singh, R. P. (1995). Heat and mass transfer in foods during deep fat frying. *Food Technology, 49*(4), 134–137.

Varnan, A. H., & Sutherland, J. P. (1995). *Meat and meat products: Technology, chemistry and microbiology* ((pp. 266–267) 26–30). New York: Chapman & Hall.

Vélez-Ruiz, J. F., & Sosa-Morales, M. E. (2003). Evaluation of physical properties of dough of donuts during deep-fat frying at different temperatures. *International Journal of Food Properties, 6*(2), 341–353.

Vélez-Ruiz, J. F., Vergara-Balderas, F. T., Sosa-Morales, M. E., & Xique-Hernández, J. (2002). Effect of temperature on the physical properties of chicken strips during deep-fat frying. *International Journal of Food Properties, 5*(1), 127–144.

Welty, J. R., Wilson, R. E., & Wicks, C. h. E. (1976). *Fundamentals of momentum, heat, and mass transfer* (pp. 561–577). New York, NY: John Wiley & Sons.