Ohmic Processing: Temperature Dependent Electrical Conductivities of Lemon Juice

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Abstract

Development of new technologies for thermal food treatment is still of great industrial and scientific interest. Ohmic heating is one of these new technologies. In this study, lemon juice was heated on a laboratory scale static ohmic at different voltage gradients in the range of 30–55V/cm. The voltage gradient was statistically significant on the ohmic heating rates for lemon juice ($P < 0.05$). Measurements were made from 20 to 74ºC and showed a linear increase in electrical conductivity values with increasing temperature. The ohmic heating system performance coefficients were in the range of 0.54–0.92.

Keywords: Ohmic heating, Electrical conductivity, Lemon juice, Temperature, Performance coefficient

1. Introduction

Ohmic heating is a thermal process in which heat is internally generated by the passage of alternating electrical current (AC) through a body such as a food system that serves as an electrical resistance (Shirsat et al., 2004). The main advantages of ohmic processing are the rapid and relatively uniform heating achieved (Zareifard et al., 2003), ease of process control, High energy efficiency (Ghnimi et al., 2008), lower degradation of vitamin (Vikram et al., 2005), together with the lower capital cost compared to other electro heating methods such as microwave and radio frequency heating (Marra et al., 2009; Kim et al., 1998). Ohmic heating is considered very suitable for thermal processing of particulates in liquid foods because the particulates heated simultaneously at similar or faster rates than the liquid.

The amount of heat generated is directly related to the current induced by the voltage gradient in the field, and the electrical conductivity (Shirsat et al., 2004). Electro-technologies for food processing are cleaner, more environmentally friendly and energy efficient than conventional methods currently in use. In addition, electrical resistance heating can intensify both heat and mass transfer (Kemp and Fryer, 2007). Ohmic heating has been shown to enhance drying rates (Wang and sastry, 2000; Zhong and Lima, 2003) and extraction yields (Wang and Sastry, 2002) in certain fruits and vegetables.

Icier and Ilicali (2005a) reported that the electrical conductivity increased linearly with increasing temperatures for fruit juices orange at voltage gradients ranging from 20 to 60V/cm. Palanippan and Sastry (1991) reported that the electrical conductivity of the orange, carrot and tomato juices increased with temperature and decreased with solids content. Icier et al (2008) similarly found that the electrical conductivity increased as the temperature increased ranging from 0.4 to 0.75S/m for fresh grap juice. Amiali et al. (2006) studied that the electrical conductivity (0.13 to 0.63S/m) increased linearly with increasing temperatures for fruit juices (namely apple, orange, and pineapple juices). The ohmic heating of fruit juice was studied at different voltage gradients (7.5 to 26.25V/cm) by Kong et al. (2008). Results indicated that the voltage gradient significantly influenced the ohmic heating rates. Also, they found that the electrical conductivity changed significantly with temperature.

The aim of this study was to obtain electrical conductivity data for lemon juice during ohmic heating over the sterilization temperatures range. Effects of temperature and voltage gradients on ohmic heating rates of lemon juice were studied. Ohmic heating of lemon juice as a single phase were also mathematically modeled by taking the system performance coefficients into account.

2. Materials and methods

2.1 samples

The fresh lemon fruits used in this study were purchased from a local market in Tehran, Iran and stored at refrigeration conditions (4°C) prior to experiments (not more than 6hr). Fruits were washed with water to remove dirt on the skin; and then the water on the skin surface was drained. For experiment, the fruits were crushed and squeezed. The juice was filtered.

2.2 Ohmic heating system

A schematic diagram of the electrical circuitry is shown in Fig. 1. The experimental device consisted of a power supply, an isolating transformer, a variable transformer, microcomputer and three digital multimeters. The cell employed was constructed from Pyrex. The distance between two electrodes was 0.05m and the diameter of the electrodes was 0.04m, resulting in a total sample volume of 53.8 ml. A K type thermocouple was inserted into the geometric center of the cell. The temperature at the center of the sample was used as the representative value, and was assumed to be spatially uniform because of its small size. The sample was sandwiched between two electrodes in the test cell. End caps, fitted with high grade stainless steel electrodes were held in place using a spring-loaded system which also served to prevent leakages. Temperature, current and voltage applied were monitored with three digital multimeter (ET-2230/2231, Minipa, China) and passed this information to the microcomputer with an RS 232 port at 1secend intervals. This allowed real-time calculation of the total power input to the sample at any given time (Kulshrestha and Sastry, 2006; Shirsat et al., 2004). The ohmic samples were heated at 30, 35, 45 and 55V/cm at 60Hz from 20ºC to final temperature of 70°C.

2.3 Electrical conductivity

Electrical conductivity (S/m) was calculated from voltage and current data using the following equation (Icier et al., 2008):

$$\sigma = LI/VA \qquad (1)$$

where σ is electrical conductivity (S/m); I is the current intensity (A), V is the voltage (V), L is the gap between the electrodes (m) and A is the electrode surface area (m^2).

2.4 Mathematical model

The energy given to the system during ohmic processing in unsteady state heat will be equal to the energy required to heat the sample plus the energy loss (Icier and Ilicali, 2005a,b):

$$E_{given} = E_{taken} + E_{loss} \qquad (2)$$

$$\sum (VIt) = m\, C_p\, (T_f - T_i) + E_{Loss} \qquad (3)$$

where C_p is specific heat capacity (J/kg.K); m is mass of the sample (kg); T_f is final temperature of the sample (ºC); Ti is initial temperature of the sample (ºC); t is time (s) Egiven is the electrical energy given to the system (J); and Eloss is the energy loss (J)

The energy loss term (E_{loss}) is the sum of the heat required to heat up the test cell, the heat loss to the surroundings by natural convection and the electrical energy which has not been converted into heat.

Since low E_{loss} would indicate, a system with a high performance, a system performance coefficient, SPC, was defined as;

$$SPC = m\, C_p\, (T_f - T_i)/\sum (VIt) \quad (4)$$

The voltage distribution within the sample for the quasi-static can be computed using the following Laplace low:

$$\nabla (\sigma \Delta V) = 0 \quad (5)$$

The average voltage gradient assuming that the voltage only changes in the axial direction can be written as:

$$\nabla V = \Delta V/L \quad (6)$$

To simplify the calculation of balance during heating, the following assumptions were made:

(i) Specific heat capacity of the lemon juice is constant within the range of temperatures considered.

(ii) SPC is constant.

The energy balance becomes:

$$SPC\, (\Delta V^2 \sigma A/L) = m\, Cp\, \partial T/\partial t \quad (7)$$

Eq. (6) was solved by the forward finite difference method numerically. The time step used in the computations was 0.01s. The physical properties used in the computations and the experimental parameters are given in Table 1. A nonlinear analysis of covariance was used to evaluate treatment combination differences. The experiments were replicated three times.

3. Results and discussion

3.1 Effect of temperature and voltage gradient

Results of the nonlinear analysis of covariance are shown in Table 2. The results indicated that that voltage gradient and temperature significantly altered (increased) the electrical conductivity value of lemon juice ($P < 0.05$).

The changes in electrical conductivity of lemon juice with temperature during ohmic heating at four different voltage gradients are given in Fig. 2. As shown in Fig. 2, the electrical conductivity increased as the temperature increased during ohmic heating. The results are similar to those reported by Kemp and Fryer (2007); Icier et al. (2008); Icier and Ilicali (2004 and 2005a, b); Li et al (2004); Zareifard et al (2003) and Tulsiyan et al (2008). Kemp and Fryer (2007); Icier et al. (2008) reported that the increase in the electrical conductivity values with temperature has been explained by reduced drag for the movement. The highest electrical conductivity was observed on 55V/cm, followed by 45, 35 and 30 V/cm. The electrical conductivity at 35 V/cm was slightly higher than that at 30 V/cm. Similar observations were reported for grape juice (Icier et al., 2008), apple and sour cherry juice (Icier and Ilicali, 2004). Between 55 and 75ºC, the electrical conductivity at 40 V/cm was slightly higher than that at 20 or 30 V/cm.

Cristina et al. (1999) reported that the electrical conductivity was dependent on the concentration (°Brix) and the temperature (20-80°C) for lemon juice. The electrical conductivity increases with increasing concentration up to approximately 30°Brix, when it starts to decrease. The decrease in electrical conductivity may be due to the increase in viscosity of the juices with concentration which decreases the mobility of the ions.

Since the experimental electrical conductivity results for the lemon juice samples given in Fig. 2 showed a linear trend with increasing temperature, a linear equation shown in Eq. (8) was used to fit the experimental data. The constants and the linear regression coefficients are given in Table 3.

$$\sigma = B\, T + C \quad (8)$$

where B and C are constant; and T is temperature (ºC). High coefficients of determination ($R^2 > 0.97$) indicate the suitability of the linear model for conductivity variation with temperature.

At high voltage gradients, the current passing through the sample was higher and this increased the heat generation rate. As the voltage gradient increased the heating time of the lemon juice required to reach the prescribed temperature decreased. Other researchers who have found a linear increase in electrical conductivity with increase in temperature include Sarang et al (2008), Tulsiyan et al (2008), Legrand et al. (2007), Icier and Ilicali (2005a,b), Castro et al (2004), Li et al (2004), Zareifard et al (2003) and Fiala et al (2001). The experimental ohmic heating times required to raise the temperatures of the lemon juice from 20 to 74ºC are given in Tables 4. The time required to heat the lemon juice from 20 to 74ºC at 30 V/cm was 1.64, 2.18 and 4 times longer than at 35, 45 and 55 V/cm, respectively. In addition to this, Icier and Ilicali (2004) reported that the decrease in the concentration of the apple and sour-cherry juices from 60% to 20% enhanced the ohmic heating rate of the juices. Icier and Ilicali (2005b) reported similarly that electrical conductivity depended on the drained the viscosity of the heated solution during ohmic heating.

3.2 Performance coefficient

The mathematical model predicted smaller heating rate, which led to higher heating time than the experimental results. The electrical energies given to the system, the heat taken by the fruit juice concentrates, performance coefficients (SPC) and heating times for mathematical model calculated for each voltage gradient experiments are shown in Table 4. For the 30 V/cm voltage gradient SPC was approximately 0.92, which indicated that 8% of the electrical energy given to the system was not used to heat up the test liquid. However, for higher voltage gradients, SPC values were lower and the heat required to heat up the test cell was too small to account for the energy loss term, Eloss. A similar observation was reported by Icier and Ilicali (2004, 2005a) for orange juice, peach puree and apricot puree.

A portion of the electrical energy input was used for physical, chemical and electrochemical changes in the concentrate. It is rather difficult to comment on the exact nature of this loss. In industrial scale production it was concluded that not all of the electrical energy was converted into heat in the lemon juice concentrate. Because a steady state will be obtained as soon the system is heated, so it will be of lesser importance. The stainless steel electrodes caused electrochemical reactions in the food sample that not beneficial (Assiry et al., 2003). They suggested that the titanium coated electrodes using ohmically heating processing, because it could decrease these reactions. Thus, the kind electrodes had different effects during ohmic heating and the amount of energy used for electrochemical reactions.

From the experimental data obtained it is clear that this loss depends on the voltage gradient applied. For low voltage gradients, the conversion of electrical energy into heat was larger. Therefore, the system was performing better. The level of agreement between the predicted and experimental heating times was relatively good when these electrical conductivity models were used.

4. Conclusion

The electrical conductivity increased linearly with increasing of temperature. The electrical conductivity of lemon juice is strongly dependent on temperature. The rate of change of temperature for 55V/cm was higher than each other voltage gradients applied. Ohmic heating times and performance coefficients are dependent on the voltage gradient used. As the voltage gradient increased, time and performance coefficient decreased. This modeling procedure can be used for designing and controlling ohmic heating processes to ensure thermal sterilization and safety of ohmically heated food products.

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Table 1. The parameters and properties used in model calculations

Property or parameter (unit)	value
Density(kg/m^3)	1071.7
Specific heat (J/kg. K)	3850

Table 2. Nonlinear analysis of covariance table for a completely randomized design with a factorial treatment structure for the lemon juice

Source	Sum of Squares	df	F
Corrected Model	5.81[a]	7	901.2
Intercept	7.63	1	8280
T	1.76	1	19.4
V	0.054	3	5153
T×V	0.129	3	46.8
Error	0.203	220	
Total	100.7	228	
Corrected Total	6.02	227	

[a] R^2 = 0.970 (Adjusted R^2 = 0.965)

Table 3. The constants and coefficients of liner model of lemon juice during ohmic heating

Voltage gradient (V/cm)	B	C	R^2
55	0.0106	0.2298	0.987
45	0.0058	0.2971	0.967
35	0.01	0.2389	0.999
30	0.0081	0.1994	0.999

Table 4. Experimental data and the model predictions of lemon juice during ohmic heating

V/cm	Q_t(J)	E_g(J)	SPC	T_i	T_f	t_{exp}	t_{adb}	t_T
30	7899	8620	0.92	19.8	73	44	44	44
35	6834	7678	0.90	19.7	73	24	22	30
45	5496	6521	0.84	20	74	18	15	24
55	4518	8382	0.54	20.3	74.7	11	11	13

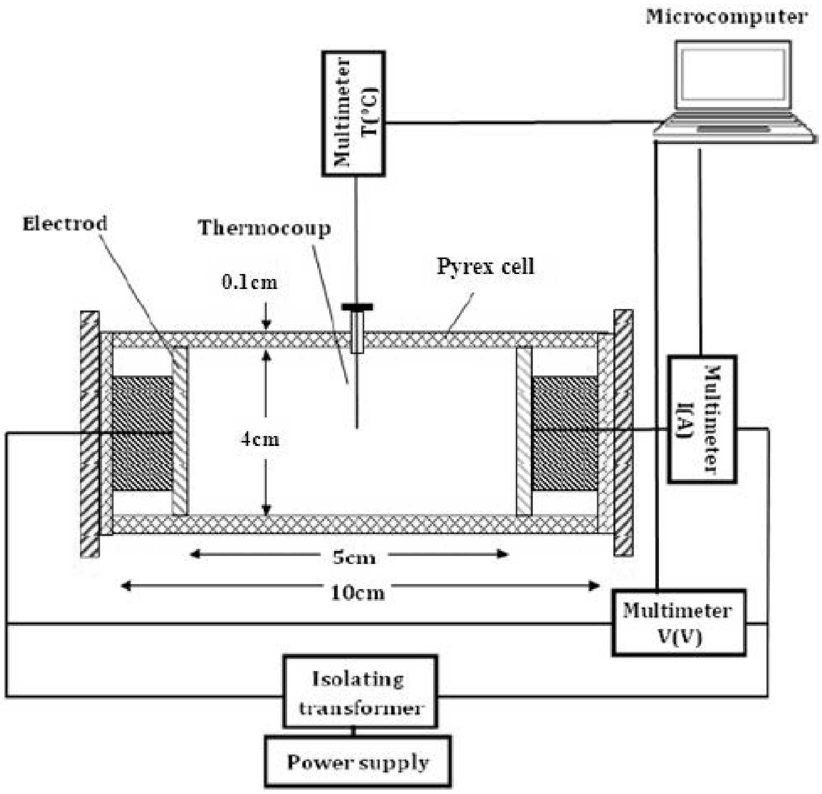

Figure 1. Schematic diagram of the ohmic heating system

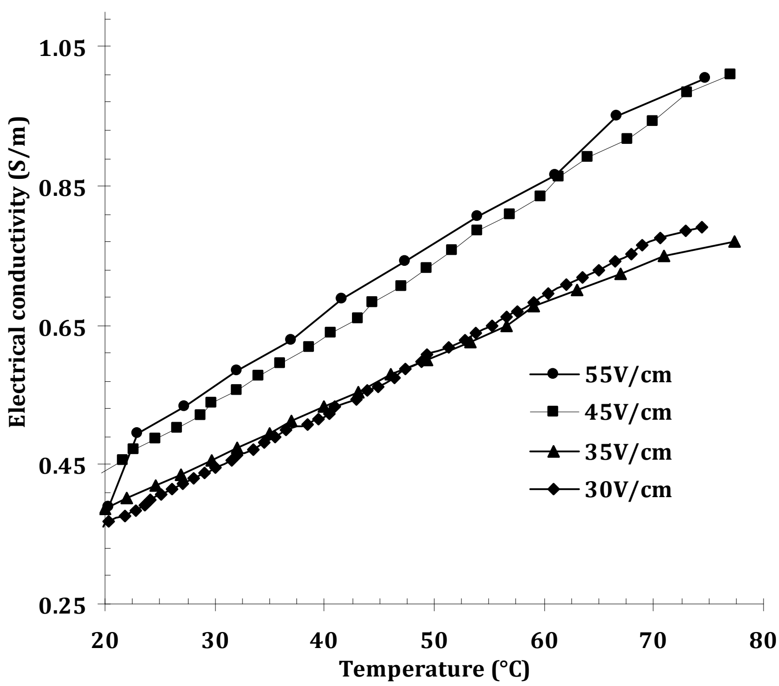

Figure 2. Electrical conductivity changes of lemon juice during ohmic heating at different voltage gradients

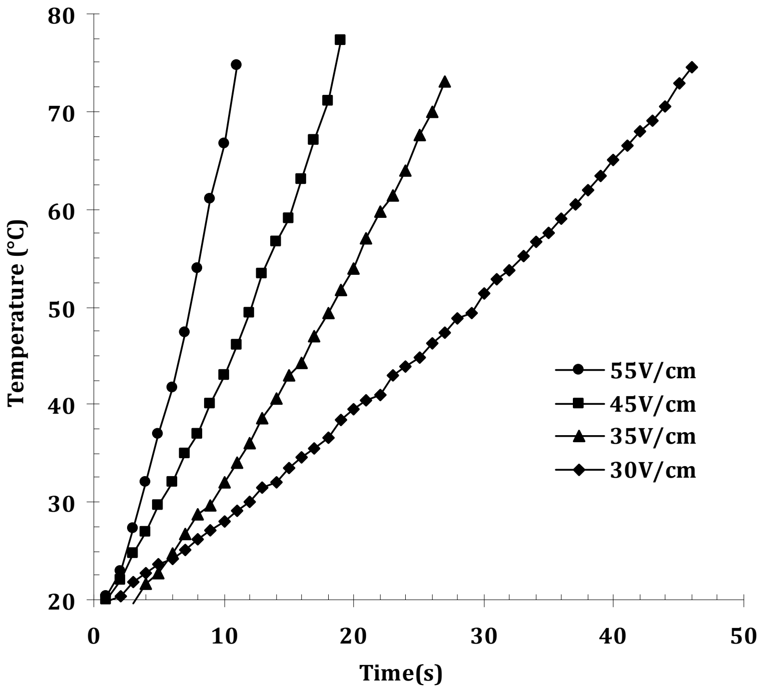

Figure 3. Ohmic heating curves of lemon juices at different voltage gradients