Ohmic Heating of *Aloe vera* Gel: Electrical Conductivity and Energy Efficiency

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ABSTRACT: *Ohmic heating is defined as a process which alternating electric current is passed through food with the primary purpose of heating it due to the electrical resistance and can be specially applied as an alternative heating method. In this research, Aloe vera gel concentrates having 0.5-2% soluble solids were ohmically heated up to 60°C by using four different voltage gradients (30–60 V/cm). The dependence of electrical conductivity on temperature, voltage gradient, and concentration were obtained. Results indicated that there was a linear relationship between temperature and electrical conductivity. The range of the electrical conductivity was 0.45 to1.20 S/m, which was dependent on the concentration and voltage gradient, although the effect of concentration was very higher than voltage gradient. The ohmic heating System Performance Coefficients (SPCs) were calculated by using the energies given to the system and taken by the Aloe vera gel samples and were in the range of 0.67- 0.89 and the highest SPC (0.89) was observed at 0.5 % and 30 V/cm.*

KEYWORDS: *Ohmic heating; Aloe vera gel; Concentration; Voltage gradient; Electrical conductivity; Energy efficiency.*

INTRODUCTION

Aloe barbadensis Miller (or *Aloe vera*) belongs to the Aloe family [1] and, is the most commercial Aloe and has many nutritional and therapeutic properties due to its gel [2]. Due to its therapeutic properties, it has often been referred to as the healing plant, miracle plant and plant of life [3].

Ohmic heating, Joule heating or direct resistance heating occurs when Alternating Current (AC) is passed through a conductive material, with the primary purpose of heating it due to the electrical resistance of the foods. Most foods contain ionic compositions such as salts and acids, therefore, electric current can be made to pass through food and generate heat inside it volumetrically [4, 5]. This technology provides rapid and uniform heating and is more environmentally friendly resulting in a high quality product with minimal changes of structural, nutritional, or organoleptic properties. The success of ohmic heating depends on the rate of heat generation and

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the electrical conductivity of the food [6, 7]. Electrical conductivity is the measure of how well a substance transmits electric charge, expressed in Siemens per centimeter (S/cm), is affected by the chemical composition (the mineral or ionic content) of a substance. *Assiry et al* (2010) [8] studied the effects of temperature, electrical field strength (voltage gradient) and the concentrations of total dissolved solids on electrical conductivity during ohmic heating of seawater. *Icier* and *Ilicali* (2004, 2005a) [9, 10] studied the dependence of electrical conductivity on temperature, voltage gradient (20–60 V/cm) and concentration (having 20-60% soluble solids) in orange juice and apple juice concentrates, respectively which were ohmically heated. Then, they calculated SPCs of the ohmic heater at different conditions.

However, studies on the concentration and temperature dependent electrical conductivity of concentrated fruit juices, and the effects of higher applied voltage gradients on the ohmic heating rate of different types of fruit juices, are limited. There is also little information on the performance aspects of ohmic heating systems of liquid foods. The aim of this research was to determine the effects of concentration (based on total soluble solids) and applied voltage gradients on the ohmic heating rates, electrical conductivity data and SPC for concentrated *Aloe vera* gel to be heated ohmically in the food industry.

EXPERIMENTAL SECTION

Sample preparation

Leaves of *Aloe vera* were provided by the experimental farm of Tarbiat Modares University, Tehran, Iran. The homogenous leaves were selected according to size, ripeness, color, and freshness. The yellow-colored liquid of *Aloe vera* was extracted by cutting the base of the leaves and allowing them to drain for 1 hour. The epidermis was separated; pulp cut into small pieces and blended in a mixer. The blended sample was filtered through a 4-fold cloth to remove every fiber and obtain a clear gel. The moisture content was determined by AOAC method no. 934.06 [11]. The initial soluble solid content of the clear gel was 0.7%. The sample was concentrated using rotary evaporator to 2 %. Different concentrations of *Aloe vera* gel (0.5, 1, 1.5 and 2 %) were prepared from the concentrate and these were used to investigate the effect of soluble solid concentration on electrical conductivity and the ohmic heating rates of the gel samples.

Ohmic heating

The present experiment was performed in a batch ohmic heater according to *Saberian et al.* (2015) [12]. *Aloe vera* gel samples were poured into the ohmic heater and the samples were heated up to 60 °C using the alternating current of 50 Hz at applied voltages of 150, 200, 250 and 300 V, corresponding to electrical field strengths of 30, 40, 50 and 60 (V/cm), respectively. The temperature at the geometric center of the sample was continuously measured with a K-Type and Teflon coated thermocouple to prevent interference from the electrical field. Voltage and current were measured using power analyzer (SW-U801-WIN, Lutron DW-6090, Taiwan). Temperature, voltage and current data were recorded on a data logger (at 1 second intervals).

Electrical conductivity

The electrical conductivity of the samples was calculated from voltage and current data using the following Equation [13];

$$\sigma = \left(LI/AV\right) \quad (1)$$

Where;

σ: electrical conductivity, [S/cm].

L: distance between electrodes, [cm].

A: area of electrode, [cm^2].

I: alternating current passing through the sample, [A].

V: voltage across the sample, [V].

The time-temperature data were plotted to obtain the ohmic heating curves for the *Aloe vera* gel concentrates. Electrical conductivity was plotted against the corresponding temperature to get the electrical conductivity curves. The electrical conductivity of the *Aloe vera* gel was modeled as a function of temperature, voltage gradient, and concentration.

The constants of the temperature dependent electrical conductivity relations for different voltage gradient and concentrations were obtained using linear regression analysis according to Eq. (2) [14]:

$$\sigma_T = \sigma_0 + bT \quad (2)$$

$\sigma_{T:}$ electrical conductivity at any temperature from 30 to 60°C, [S/cm].

$\sigma_{0:}$ initial electrical conductivity, [S/cm].

b: temperature factor [S/cm °C].

To determine the effect of temperature, voltage gradient and concentration on the electrical conductivity, an electrical conductivity equation, which can be used in the all temperature, concentration, and voltage gradient ranges, was investigated. In addition to R^2, the Root Mean Square Error (RMSE) and χ^2 (Chi-square) of the predicted model were calculated according to Eqs. (3) and (4), to verify the model.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\sigma_{pre} - \sigma_{exp}\right)^2} \tag{3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\sigma_{exp} - \sigma_{pre}\right)^2}{N - m} \tag{4}$$

Where *N* is the number of observations, *m* is the number of constants, σ_{exp} and σ_{exp} are the predicted and experimental electrical conductivity, respectively [15].

The energy given to the system was calculated by using the current and voltage values recorded during the ohmic heating experiments according to Eq. (5) [16]:

$$E_g = \sum VIt \tag{5}$$

Where E_g is the energy given to the system and t is time (s).The heat required to heat the sample to 60°C was calculated as [9]:

$$Q_t = mC_p\left(T_f - T_i\right) \tag{6}$$

Where *Q* is the amount of heat taken by the system (J), T_f is final temperature and T_i is initial temperature (°C), C_p is specific heat capacity (J/kg K) and *m* is mass of the sample (kg).

The specific heat capacities of the *Aloe vera* concentrates were assumed to be independent of temperature and calculated according to Eq. (7) [17]:

$$C_p = 1.675 + 2.5X_w \tag{7}$$

Which X_w is a percent of the moisture. The energy given to the system will be equal to the energy required to heat the sample plus the energy loss according to the following equation [10]:

$$E_g = Q_t + E_{loss} \tag{8}$$

The E_{loss} term in Eq. (8) represents the heat required to heat the test chamber, the electrodes, etc., heat loss to the surroundings by natural convection and the part of the heat generation rate used for goals other than heating the juice for example in a chemical reaction, phase change.

The total energy loss during ohmic heating, E_{loss}, was calculated by using the energy given to the system and the heat required to heat the sample to a distinct temperature.

Since low E_{loss} would display a system with high performance, a System Performance Coefficient (SPC) was defined as the following equation [18]:

$$\mathrm{SPC} = \left(Q_t / E_g\right) \tag{9}$$

For a system with zero E_{loss}, SPC will be equal to one.

Statistical analysis

Results were analyzed by analysis of variance (ANOVA) using SAS 9.1 and Curve Expert 1.3 Statistical Softwares. Full factorial design and LSD test with 95% confidence interval were used to compare the means of the tests. The results presented in this manuscript have been obtained from the average values of the three replicate experiments.

RESULTS AND DISCUSSION

Ohmic heating rate

In this study, Ohmic heating curves of *Aloe vera* gel concentrate having 0.5-2% soluble solids at four different voltage gradients (30–60 V/cm) were plotted and the data were obtained. As Table 1 shown, ohmic heating of *Aloe vera* gel during the time was linear and the range of heating rate was 0.779 to 5.471 °C/s which depended on voltage gradient and concentration of soluble solid of gel.

Assiry et al. (2010) [8] reported that the range of the concentration of the Total Dissolved Solids (TDS) and the voltage gradient. As shown in Figs. 1 and 2, as voltage gradient and concentration of soluble solid, were increased, the heating rates also were increased, so that the highest heating rate was related to the highest voltage gradient and concentrate (60 V/cm and 2%) resulting the lowest time for heating of gel. According to Table 1, the effect of a voltage gradient on the heating rate was higher than concentration because with increasing of concentration from 0.5 to 1% at 30 V/cm, the heating rate was increased

Table 1: The ohmic heating rate of Aloe vera gel at the different voltage gradient and concentrations.

Voltage gradient	Concentration	dT/dt	R^2
(V/cm)	(%)	(s/°C)	-
30	0.5	0.779	0.998
	1	1.21	0.994
	1.5	1.304	0.994
	2	1.421	0.989
40	0.5	1.456	0.994
	1	1.898	0.993
	1.5	2.031	0.992
	2	2.903	0.982
50	0.5	2.036	0.989
	1	2.647	0.989
	1.5	3.88	0.974
	2	4.912	0.959
60	0.5	2.956	0.972
	1	3.81	0.993
	1.5	4.787	0.949
	2	5.471	0.946

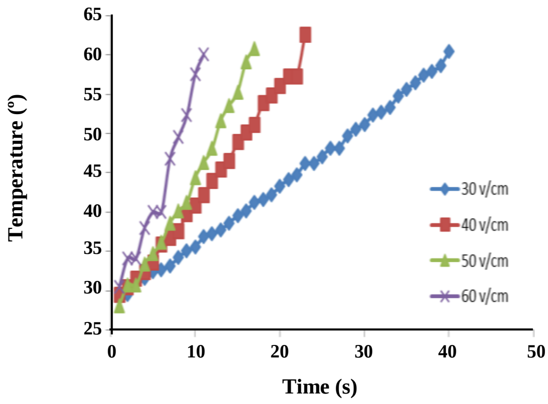

Fig. 1: Ohmic heating curves of Aloe vera gel at 0.5% concentration at different voltage gradients (30-60 V/cm).

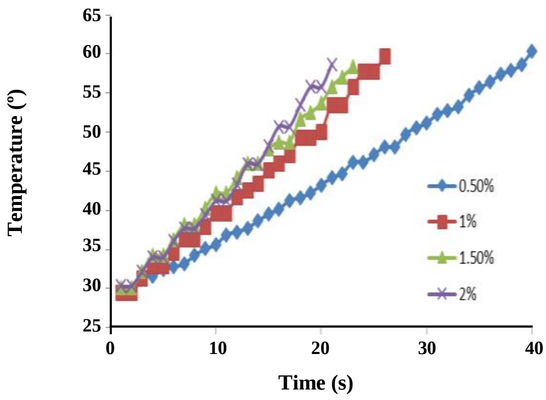

Fig. 2: Ohmic heating curves of Aloe vera gel concentrate (0.5-2%) at 30 V/cm.

1.55 times but increasing voltage gradient from 30 to 60 V/cm at 0.5%, increased heating rate 3.8 times. Therefore, doubling of voltage gradient than concentration has a higher effect on the heating rate. Also, *Hong et al.* (1998) [19] and *Darvishi et al.* (2013) [20] reported that the heating rate was highly dependent on the applied voltage gradient.

Electrical conductivity during ohmic heating

Electrical conductivity is a critical parameter in ohmic heating and thus, the ohmic heating rate is directly dependent on it [21]. Therefore, designing an ohmic heating system for beverage pasteurization is dependent on understanding its electrical conductivity [22]. Electrical conductivity values of the gel concentrates were

Table 2: Temperature-dependent electrical conductivity of Aloe vera gel at the different concentrations and voltage gradients.

Concentration	Voltage gradient	Electrical conductivity–temperature	R^2
(%)	(v/cm)	$\sigma = b.T \pm \sigma_0$ (S/m)	
0.5	30	σ = 0.0063 T ± 0.142	0.997
	40	σ = 0.0066 T ± 0.158	0.991
	50	σ = 0.0067 T ± 0.15	0.995
	60	σ = 0.0072 T ± 0.18	0.981
1	30	σ = 0.0116 T ± 0.26	0.996
	40	σ = 0.011 T ± 0.296	0.992
	50	σ = 0.0121 T ± 0.27	0.914
	60	σ = 0.0133 T ± 0.263	0.974
1.5	30	σ = 0.0095 T ± 0.544	0.776
	40	σ = 0.0116 T ± 0.43	0.782
	50	σ = 0.0143 T ± 0.4	0.915
	60	σ = 0.0131 T ± 0.504	0.918
2	30	σ = 0.0236 T ± 0.046	0.548
	40	σ = 0.0184 T ± 0.44	0.895
	50	σ = 0.0163 T ± 0.536	0.804
	60	σ = 0.0205 T ± 0.413	0.876

calculated by Eq. (1) using the recorded voltage and ampere data during ohmic heating.

Results showed that the electrical conductivity was depending on the temperature, voltage gradient and concentration ($P < 0.05$). The interaction effect of these parameters on the electrical conductivity was not significant ($P > 0.05$). As illustrated in Table 2, the relationships between temperature and electrical conductivity for each concentration and voltage gradient applied were linear with relatively good fitting (R^2 near to one). By increasing of temperature, electrical conductivity values increased. *Qihua et al.* (1993) [23] also observed a linear relationship between temperature and electrical conductivity of orange juice. *Castro et al.* (2003) [16] found that the electrical conductivity of strawberry-based products increased with temperature as linear or quadratic relations depending on product type tested. Increase in the electrical conductivity values with temperature has been attributed to reduced drag and enhanced mobility for the movement of ions [24]. *Icier* and *Ilicali* (2004) [9] reported that the electrical conductivity values of apple and sour cherry juice concentrates have shown the increasing trend with the temperature at all voltage gradients studied.

Voltage gradient had affected the electrical conductivity significantly ($P < 0.05$) as shown in Table 3. Increasing of voltage gradient from 30 to 40 V/cm had not any significant effect on the electrical conductivity but at 50 and 60 V /cm, the electrical conductivities were significantly higher than other voltage gradients. *Darvishi et al.* (2011) [25] and *Icier* (2003) [18] reported that electrical conductivity was increased significantly by increasing of voltage gradient applied during ohmic heating on lemon and grape juice, respectively.

According to Table 4, concentration has a significant positive effect ($P < 0.05$) on the electrical conductivity. *Assiry et al.* (2010) [8] reported that temperature and concentration have a positive relation with the electrical conductivity but the concentration has more effect on the electrical conductivity than the temperature, especially at high concentrations. *Icier* and *Ilicali* (2005b) [26] indicated that at a special voltage gradient and

Table 3: The effect of voltage gradients on the electrical conductivity.

voltage gradient (V /cm)	Electrical conductivity ± SD (S/m)
30	0.814 ± 0.031 [b]
40	0.843 ± 0.035 [b]
50	0.884 ± 0.032 [a]
60	0.910 ± 0.029 [a]

Table 4: The effect of concentration on the electrical conductivity.

Concentration (%)	Electrical conductivity ± SD (S/m)
0.5	0.450 ± 0.067 [d]
1	0.802 ± 0.119 [c]
1.5	0.992 ± 0.131 [b]
2	1.206 ± 0.182 [a]

temperature, by increasing of orange juice concentration from 20 to 60%, the electrical conductivity was decreased and thereby the heating rate was decreased and therefore, the time of heating was increased. *Palaniappan* and *Sastry* (1991b) [27] reported that the electrical conductivities of juices increased linearly by decreasing insoluble solid contents, whereas a nonlinear relationship was obtained in this study. *Castro et al.* (2003) [17] suggested that the electrical conductivity decreases with increasing of solids and sugar content of strawberry-based products. They stated that the concentration dependency of the electrical conductivity of the juices can be explained by the decreased mobility of ions by increasing concentration.

The reason for the differences between the effects of solids contents obtained in this research and the literature may be explained by the nature of the solutes in the samples tested. Some components may affect the electrical conductivity of the sample, depending on their electrolytic characteristics. In fruit juices, the major solute component is the sugar having non electrolytic behavior. As the sugar content increases, the electrical conductivities of the juices decrease. Also, the acidity and ionic salts of the juices enhance the electrical conductivity, therefore, sugar content and the nature of the other components may cause different electrical conductivities in the juice samples (*Icier*, 2003) [18].

Considering this fact that the electrical conductivity was strongly influenced by concentration (Table 4) and also, significant part of *Aloe vera* gel components is consisted of inorganic salts (*Reynolds*, 2004) [2], increasing of electrical conductivity with gel concentration (which observed in this research) can be attributed to concentration of inorganic salts, which had been increased. *Icier* and *Ilicali* (2004) [9] reported that the electrical conductivity values of sour cherry juice were higher than the apple juice for the same temperature at all concentrations and for all voltage gradients applied. They resulted that this was attributed to the higher acid content of the sour cherry juice having similar insoluble solid content with the apple juice which confirms this explains.

Considering that the electrical conductivity was influenced by temperature, voltage gradient and concentration, an electrical conductivity equation, which has practical importance in the design of ohmic heaters, was investigated. This equation was given as Eq. (9).

$$\sigma = A.T + (\text{Concentration})^{N1} + (\text{Voltage gradient})^{N2} \quad (9)$$

The nonlinear regression equation constants and multiple regression coefficients obtained by using Curve Expert 1.3 software are given in Table 5 to determine the effect of these parameters on the electrical conductivity.

As shown in Table 5, R^2 was high (0.962) and the values of the root mean square error (RMSE) and χ^2 were very low. Therefore, the model can predict the electrical conductivity appropriately. In addition, the coefficient of concentration (N1) was larger than the coefficient of voltage gradient (N2) which can result that the effect of concentration is more than of voltage gradient on the electric conductivity.

SPC

The electrical energies are given to the system and the heat energies taken up by the gel concentrate were calculated using the experimental data, and SPCs calculated for each ohmic heating experiment are also shown in Tables 6 and 7. SPCs were in the range of 0.67-0.89 (data not showed), which display that approximately 11-33% of the electrical energy given to the system, was not utilized by the gel. SPC was affected significantly (*P* < 0.05) by voltage gradient and concentration although the interaction effect of the voltage gradient and

Table 5: General electrical conductivity equation constants for Aloe vera gel concentrate.

(σ= A.T + (Concentration) ^{N1} + (Voltage Gradient) ^{N2} + B)						
A	N1	N2	B	R^2	RMSE	χ^2
1.09×10^{-2}	0.278	0.0945	-3.018	0.962	0.00517	0.00032

A and B are constants and N1 and N2 are exponents of equation.

Table 6: The effect of voltage gradients on the SPC.

voltage gradient (V/cm)	SPC (%)
30	78.3 $\pm$ 2.3 ^{a}
40	77.6 $\pm$ 3.1 ^{a}
50	75.4 $\pm$ 2.5 ^{ab}
60	71.1 $\pm$ 2.6 ^{b}

Table 7: The effect of concentration on the SPC.

Concentration (%)	SPC (%)
0.5	85.6 $\pm$ 3.2 ^{a}
1	72.4 $\pm$ 2.1 ^{b}
1.5	71.0$\pm$ 2.5 ^{b}
2	73.3 $\pm$ 3.2 ^{b}

concentration on the electrical conductivity was not significant *(P* > 0.05). Decreasing the concentration and voltage gradient enhanced SPC, therefore the highest SPC was observed at 30 V/cm and 0.5% concentration.

Icier and *Ilicali* (2004) [9] reported that the SPCs depend significantly on the voltage gradient applied and the lowest SPC was observed at the highest voltage gradient. They stated that at 60 V/cm, SPCs were in the range of 0.6-0.7 for apple juice and 0.5-0.6 for sour cherry juice concentrates. At low concentrations of the gel for 30 V/cm, SPCs were close to unity (0.89) indicating minimum loss and so the system was performing better, which was in agreement with *Icier* and *Ilicali* (2005a, b) [10, 26] and *Darvishi et al.* (2013) [20]. *Assiry et al.* (2003) [28] reported that energy losses can be mostly explained by the energies used for the purposes of physical (e.g. heating of ohmic cell), chemical and electrochemical changes during heating). They also stated that the increase in the voltage gradient applied in the range of 20–70 V/cm was statistically significant in the energy losses during ohmic heating. *Mercali et al.* (2014) [21] reported that at higher voltage gradient, electrochemical reactions increase. *Assiry et al.* (2003) [28] and *Zhao* and *Kolbe* (1999) [29] stated that stainless steel electrodes caused the electrochemical reactions in the food sample. They concluded that the titanium coated electrodes could reduce these reactions and thereby the amount of energy used for electrochemical reactions in comparison to the stainless steel. *Samaranayake* (2003) [30] reported that platinized titanium had the most inert electrochemical behavior at different pH during ohmic heating. *Saberian et al.* (2017) [31] observed that the highest SPC occurred at 30 V/cm (the highest applied voltage gradient) which could be attributed to the platinum electrode because the electrochemical reaction and time of heating were minimum. *Darviiishi et al.* (2015) [32] and *Icier* and *Ilicali* (2005a) [10] concluded that the heat loss to the surroundings by natural convection was assumed to be very small and therefore it was negligible but the heat required to heat up the test chamber was estimated to be around 2–14% of the energy given to the system.

It is very difficult to comment on the exact nature of the energy loss but it can be concluded that in this research, the electrochemical reactions of the stainless steel electrodes and the heating up the test cell were the main reasons for the energy loss.

CONCLUSIONS

Ohmic heating times were dependent on the concentration and voltage gradient applied, so that as the concentration and voltage gradient were increased, the time of heating was decreased. Determination of the electrical conductivity and SPC during ohmic heating is very important in designing of ohmic heaters. The electrical conductivity of *Aloe vera* gel increased with temperature, concentration and voltage gradient during ohmic heating. Unlike other researcher's results, the concentration of the gel had a positive effect on the electrical conductivity because of the electrolytic characteristic of gel components. Furthermore, the model showed that the effect of the concentration was more than the effect of the voltage gradient on the electric conductivity. Reducing the concentration and voltage gradient enhanced SPC and the best SPC (0.89) occurred at the lowest concentration and voltage gradient. Therefore, ohmic heating (by stainless steel electrodes) as a novel processing method, at lower concentration and voltae gradient, is an energy efficient method.

Nomenclature

A	Contact area between sample and electrode, m^2
C_p	Specific heat capacity, J/kg K
E_g	Energy given to the system
E_{loss}	Energy loss, J
I	Alternating current passing through the sample, Amper
L	Distance between electrodes, cm
b	Temperature factor, S/cm °C
m	Mass of the sample, kg
Q	The amount of heat taken by system, J
SPC	System performance coefficient, %
T	Time, s
T_f	Final temperature, °C
T_i	Initial temperature, °C
V	Voltage across the sample, V
X_w	Percent of the moisture, %
σ	Electrical conductivity, S/cm
σ_T	Electrical conductivity at any temperature from 25 to 90°C, S/cm
σ_0	Initial electrical conductivity, S/cm

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