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Exergy and energy analyses of liquid food in an Ohmic heating process: A case study of tomato production

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ABSTRACT

Six different voltage gradients ranging from 6 to 16 V/cm were used to evaporate water from tomato samples of 9.3 (kg water/kg dry matter) to a safer level of 2.3 (kg water/kg dry matter). Energy efficiency decreased from 100 to 55.53% with decreasing moisture content and increasing voltage gradient, while, exergy efficiency increased from 3 to 83.51% with decrease in moisture content ($P < 0.05$). Average energy and exergy efficiency were found to be in the range of 67.07–85.40% and 27.75–60.34%, respectively. The electrical conductivity increased (2.36–12.38 S/m) with a decrease in moisture content and voltage gradient up to the boiling point. Specific energy consumption and average improvement potential decreased from 4.64 to 2.73 MJ/kg of water evaporation and 14.18–2.82 kW with increasing voltage gradient, respectively. The values of energy and exergy losses increased from 6.88 to 21.48 kW and 6.81–21.47 kW, respectively, as the voltage gradient and moisture content decreased.

Industrial relevance: Due to the ability of the ohmic heating technologies to achieve rapid and reasonably uniform heating of electrically conductive materials its impact on food quality is of interest. Based on literature review, in ohmic heating process it could be possible to obtain efficiencies greater than 90% in an industrial process in which these losses were controlled by the wall insulation. However there is limited information on the exergy analysis of ohmic processes and systems, to the best of the authors' knowledge. Exergy analysis becomes more crucial, especially for the industrial (large-scale) high temperature heating applications, and it can reveal whether or not and by how much it is possible to design more efficient thermal systems by reducing the sources of existing inefficiencies. This paper deals with the performance evaluation of ohmic heating process by applying exergy analysis.

1. Introduction

In ohmic heating, there is no need to transfer heat through solid-liquid interfaces or inside solid particles once the energy is dissipated directly into the foods. Ohmic heating of food products involves the direct application of alternating current in order to generate internal heat as the result of electrical resistance (Chen, Abdelrahim, & Beckerich, 2010; Zhu, Zareifard, Chen, Marcotte, & Grabowski, 2010). Its advantages compared to conventional heating include a more uniform and faster heating, higher energy efficiency, technical simplicity and low capital and maintenance cost, and higher retention of the nutritional value of food (Marra, Zell, Lyng, Morgan, & Cronin, 2009; Stancl & Zitny, 2010; Vikram, Ramesh, & Prapulla, 2005).

Food is most suitable for ohmic heating containing water and ionic salts in abundance (Sarang, Sastry, & Knipe, 2008). Ohmic heating has tremendous potential in food processing with use in preheating (Hosainpour, Nargesi, Darvishi, & Fadavi, 2014), blanching (Allali, Marchal, & Vorobiev, 2010), cooking (Bozkurt & Icier, 2010; Liu, Jayasingh, Gao, & Farid, 2007; Ozkan, Ho, & Farid, 2004), sterilization and extraction (Darvishi, Khoshtaghaza, & Najafi, 2013; Sarang et al., 2008), evaporation and dehydration (Assiry, Galiy, Alsamee, & Sarifudin, 2010; Lebovka, Shynkaryk, & Vorobiev, 2006; Zhong & Lima, 2003).

In recent years, thermodynamic analyses, particularly exergy analyses, have appeared to be an essential tool for the system design, analyses and the optimization of thermal systems. From the thermodynamics point of view, exergy is defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment (Akpinar, Midilli, & Bicer, 2006; Prommas, Rattanadecho, & Jindarat, 2012).

Based on the authors' best knowledge, several studies in which covering the energy and exergy analyses of food products especially during drying process have been undertaken, but very little information is available on the exergy and energy analyses of the ohmic heating of fluid food (Bozkurt & Icier, 2009, 2010). A comprehensive review on exergy analysis of drying processes and systems was provided by Aghbashlo, Mobli, Rafiee, and Madadlou (2013).

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Nomenclature

A	contact area between sample and electrode (m^2)
C_p	heat capacity (J/kg K)
D	outer diameter of ohmic cell (m)
$E_{electrical}$	electricity energy (J)
E	energy (J)
E_{loss}	energy loss (J)
E_s	amount of electrical energy in the form of heat (J)
E_{sc}	specific energy consumption (J/kg water)
EX	exergy (J)
ex	specific exergy (J/kg water)
EX_{loss}	exergy loss (J)
F(M)	function of moisture content
F_{ave}	average value of F(M)
I	current intensity (A)
IP	improvement potential (J)
L	gap between electrodes (m)
m	mass (kg)
M	moisture content (kg water/kg dry matter)
M_t	moisture content at any time (kg water/kg dry matter)
P_0	ambient pressure (Pa)
R^2	coefficient of determination (-)
T	temperature (K)
t	time (s)
T_{ref}	ambient temperature (K)
V	voltage (V)
η_{en}	energy efficiency (%)
η_{ex}	exergy efficiency (%)
λ_w	latent heat of pure water (J/kg)
λ_{wp}	latent heat of sample (J/kg)
ν	volume of sample (m^3)
σ	electrical conductivity (S/m)
∇V	voltage gradient (V/cm)

Subscripts

0	initial
in	inlet
out	outlet
p	product
ew	water evaporated
∞	ambient
nc	natural convection
c	ohmic cell
e	electrode
wc	outer wall of ohmic cell
ave	average value

Bozkurt and Icier (2010) performed an exergy analysis of ohmic cooking of ground beef in an ohmic heater. They reported that the energy and exergy efficiency values for ohmic cooking process at the voltage gradients between 20 and 40 V/cm were in the range of 0.69–0.91% and 63.2–89.2%, respectively.

Bozkurt and Icier (2009) used the exergy efficiency as a response in the optimization of the ohmic cooking process of beef-fat blends and reported that the exergetic efficiency of the ohmic cooking process at desired optimum conditions was 89.7%.

Energy and exergy analyses of ohmic heating system of liquid food present a novel approach to the performance evaluation of ohmic systems, which could be especially used in the industrial implementation of these systems. The objectives of this study were to present energy and exergy analyses of ohmic heating of liquid food and to estimate the improvement potential of the ohmic heating process.

2. Materials and methods

2.1. Materials

Fresh tomatoes were purchased from a local market in Ilam, Iran. Before the study, the fruits were selected by visual observation of colour and physical damage. After washing with tap water and removal of surface water using absorbent paper, crushed 0.03 g/g salt (3% NaCl salts) was added and then mixed at medium speed in a Sunny mixer (Model SEP-1010). Tomato samples had an initial moisture content of 9.3 ± 0.12% (kg water/kg dry matter), which was determined by a standard oven method at 103 ± 1 °C for 24 h (Hosainpour et al., 2014).

2.2. Experimental apparatus

Experiments were carried out in a static ohmic heating system as shown in Fig. 1. The system consisted of a cylindrical Teflon cell (inner diameter: 50 mm; wall thickness: 10 mm; length: 150 mm), two stainless steel electrodes (diameter: 49.5 mm; thickness: 2 mm) with a 50-mm gap, a power control unit (3 kW, 0–300 V, 50 Hz, MST – 3, Toyo, Japan), power analyzer (Lutron DW-6090), K-type thermocouple (Teflon-coated) and a microcomputer (Fig. 1). A hole with 2 cm in diameter was created on the surface of the cell to insert a thermocouple and allow vapor release. A digital balance (A&D GF600, Japan) with accuracy of ±0.01 g was positioned under the cell for mass determination (recording at 1- s intervals), and the instantaneous moisture content was computed using Eq. 1 (Torki-Harchegani, Ghanbarian, & Sadeghi, 2014; Usub et al., 2010):

$$M_t = \left(\frac{(1+M_0)\times m_0}{m_t} - 1\right) \tag{1}$$

The sample (25 ± 0.50 g) was placed in the cell; the thermocouples were inserted and fitted into the geometric center of the sample. Heating was stopped when the moisture content of the samples was about 2.3 ± 0.15 (kg water/kg dry matter). The electrodes were thoroughly rinsed using a brush and dematerialized with twice-distilled water after each run. The ohmic system was operated at six voltage gradients, 6, 8, 10, 12, 14, and 16 V/cm. The reference dead state conditions were considered as $T_\infty = 20$ °C and $P_0 = 101.325$ kPa.

2.3. Energy Analyze

The conservation of mass and energy for the control volume (ohmic cell) of ohmic heating is shown in Fig. 2. The general equation of mass conservation of moisture can be expressed as:

$$\begin{gathered}\sum m_{in} = \sum m_{out}\\ m_{in} = m_{ew} + m_p\end{gathered} \tag{2}$$

The general energy balance can be expressed below as the total energy inputs equal to total energy outputs:

$$\begin{gathered}\sum E_{in} = \sum E_{out}\\ (mC_pT)_{in} + E_{electrical} = (mC_p \times T)_p + m_{ew}\lambda_{wp} + E_{loss}\end{gathered} \tag{3}$$

Latent heat of product was calculated according to the following equation (Abdelmotaleb, El-Kholy, Abou-El-Hana, & Younis, 2009; Hall, 1975; Sharqawy, John, & Syed, 2010):

$$\frac{\lambda_{wp}}{\lambda_w} = 1 + 23 \times \exp(-40M_t)\ M \geq 0.9\left(\frac{\text{kg water}}{\text{kg dry matter}}\right) \tag{4}$$

$$\begin{aligned}\lambda_w = {} & 3.217 \times 10^6 - 2.631 \times 10^3\, T - 2.40T^2 + 1.460\\ & \times 10^{-2}T^3 - 2.079 \times 10^{-5}\, T^4 \quad 273 \leq T \leq 473\ K\end{aligned} \tag{5}$$

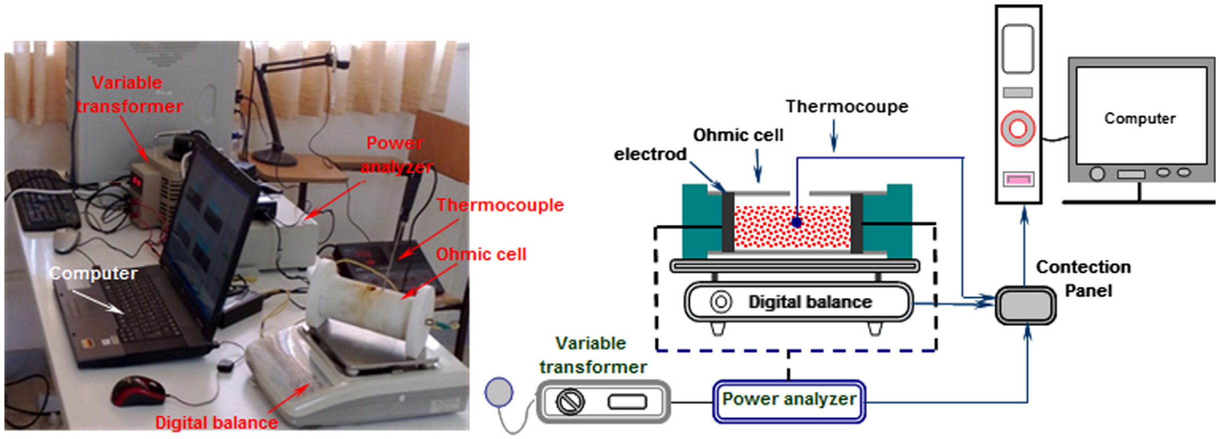

Fig. 1. Experimental apparatus.

The heat capacity of tomato is also a function of its moisture content and calculated by the Siebel's model (Heldman, 2003):

$$C_p = 0.71 + 3.39 \times \overbrace{\left(\frac{M_t}{1+M_t}\right)}^{\text{mass fraction of water}} \quad 1.86 \le M_t \le 19\left(\frac{\text{kg water}}{\text{kg dry matter}}\right), \; T > 273\text{ K} \tag{6}$$

The energy given to the system was calculated by using the current and voltage values recorded during the heating experiments:

$$E_{electrical} = \int_0^t (V \times I)dt \tag{7}$$

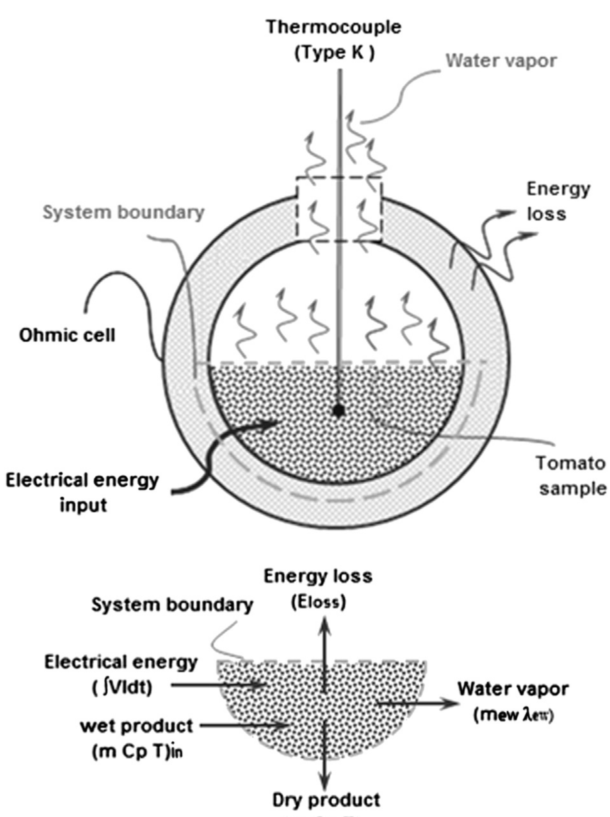

Fig. 2. Volume control of ohmic heating system.

The energy efficiency of the ohmic heating system was determined in Eq. (8);

$$\eta_{en} = 100 \times \left(\frac{(mC_p \times T)_p + m_{ew}\lambda_{wp}}{(mC_pT)_{in} + E_{electrical}}\right) \tag{8}$$

The energy loss term in Eq. (3) is the sum of the heat required to heat up the test cell; the energies used for the purposes of physical, chemical and electrochemical changes during heating; the heat loss to the surroundings by natural convection; and the electrical energy which has not been converted into heat (Assiry, Sastry, & Samaranayake, 2003; Icier & Ilicali, 2005b). The heat loss to the surroundings by natural convection (Eq. 9) and the heat required heat-up the test cell and electrodes (Eq. 10) were calculated from the following equations (Icier & Ilicali, 2005b):

$$E_{nc-loss} = 1.32\left(\frac{\Delta T}{D}\right)^{\frac{1}{4}} \pi DL\left(\overline{T}_{wc} - T_\infty\right)\Delta t \tag{9}$$

$$E_{(c+e)-loss} = \overbrace{m_cC_p\Delta T}^{\text{heat up the test cell}} + 2 \times \overbrace{m_eC_p\Delta T}^{\text{heat up the electrode}} \tag{10}$$

2.4. Second law analysis: exergy

In the scope of the second law analysis, the total exergy inflow, outflow and losses of the ohmic heating system were estimated. The general form of the total exergy equation of an ohmic system is given by:

$$\begin{aligned}&\sum EX_{in} = \sum EX_{out}\\&m_{in}ex_{in} + E_{electricity} = m_pex_p + m_{ew}ex_{wp} + EX_{loss}\end{aligned} \tag{11}$$

The exergy loss is determined by:

$$ex_{loss} = EX_{in} - EX_{out} \tag{12}$$

The specific exergy of the components at the inlet and the outlet of the ohmic heating system are determined by (Chowdhury, Bala, & Haque, 2011):

$$ex = C_p\left[(T - T_\infty) - T_\infty \ln\left(\frac{T}{T_\infty}\right)\right] \tag{13}$$

The exergy efficiency of ohmic system can be calculated using the following equation:

$$\eta_{ex} = 100 \times \left(\frac{m_pex_p + m_{ew}ex_{ew}}{m_{in}ex_{in} + E_{electricity}}\right) \tag{14}$$

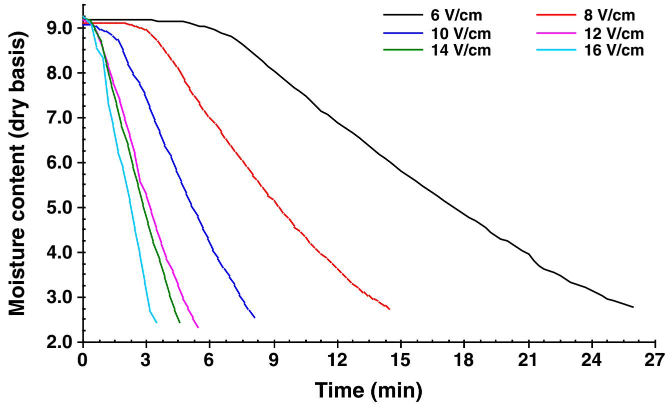

Fig. 3. Variations of moisture content as a function of time for different voltage gradient.

Van Gool (1997) proposed that maximum improvement in the exergy efficiency of a process or system was obviously achieved when the exergy loss or irreversibility was minimized. Consequently, it was suggested to use the concept of an exergetic "improvement potential" when analyzing different processes or sectors of the economy and this improvement potential in the rating form was given by Hammond and Stapleton (2001).

$$IP = (1-\eta_{ex}) \times (EX_{in} - EX_{ou}) \tag{15}$$

2.5. Electrical conductivity

The electrical conductivity was determined from the resistance of the sample and the geometry of the cell using the following equation:

$$\sigma = \frac{L}{AR} = \frac{LI}{AV} \tag{16}$$

During heating, the contact area between sample and electrodes decreased due evaporation process. Thus, the contact area can be calculated as follows:

$$A = \frac{m_t}{\rho_t L} \tag{17}$$

$$\rho_t = 1340 - 3.26M_t^2 \tag{18}$$

Density of tomato samples at difference moisture contents determined by applying the standard volumetric pycnometer (Darvishi et al., 2013). The sample kept in a 50 ml standard volumetric pycnometer was weighed using a digital balance (A&D GF 600, Japan) with an accuracy of ±0.001 g. Density is calculated using the below formula:

$$\rho_t = \frac{\text{mass of sample}}{\text{volume of pycnometer}} \tag{19}$$

2.6. Statistical analysis

Heating tests were replicated three times at each voltage gradient, and averages are reported with standard deviation. The statistical evaluation was performed by using SPSS software Ver.18. The comparison of the results was made to analyze the effect of voltage gradient on selected properties by using one-way ANOVA and post hoc (Duncan) tests. All statistical significance was determined at the 5% significance level ($P < 0.05$). The average value of each parameter was calculated using the following expression (Celma, Cuadros, & Rodriguez, 2012):

$$F_{ave} = \frac{\int_{M_{initial}}^{M_{final}} F(M).\, dM}{\int_{M_{initial}}^{M_{final}} dM} \tag{20}$$

3. Result and Discussion

3.1. Mass balance and heating rate

Fig. 3 presents the variations of moisture content as a function of drying time at voltage gradients of 6–16 V/cm. It was noticed from these curves that the voltage gradient affected the drying rates of samples. The total heating times to reach the final moisture content of the tomato samples were 25.42, 12.88, 8.37, 5.62, 4.65 and 3.55 min at 6, 8, 10, 12, 14, and 16 V/cm, respectively. As voltage gradient was increased from 6 to 16 V/cm, the heating time was reduced by about 90%. The effect of voltage gradient on the temperature of the process is shown in Fig. 4. After an initial short period which practically coincided with the warming-up period, the temperature reached a maximum value and then gradually remained constant throughout the heating process. This is because the latent heat transfer due to evaporation is retained due to the decline in the evaporation rate together with the decreases of average moisture content. At high voltage gradients, the current passing through the sample and local electrical field strength were higher. As a result the dissipation of electrical energy as heat increased which caused a higher water evaporation rate within the sample (Goullieux & Pain,

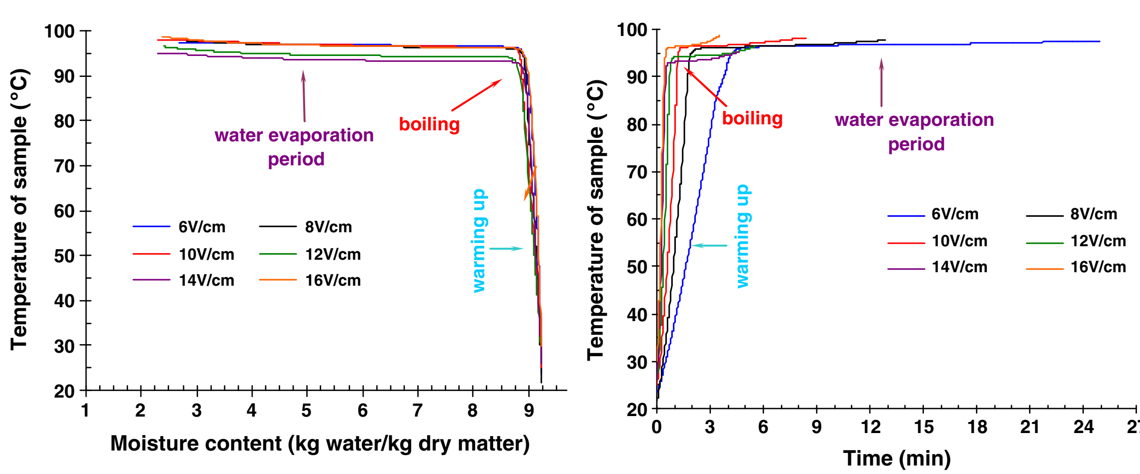

Fig. 4. Temperature of tomato samples during ohmic heating.

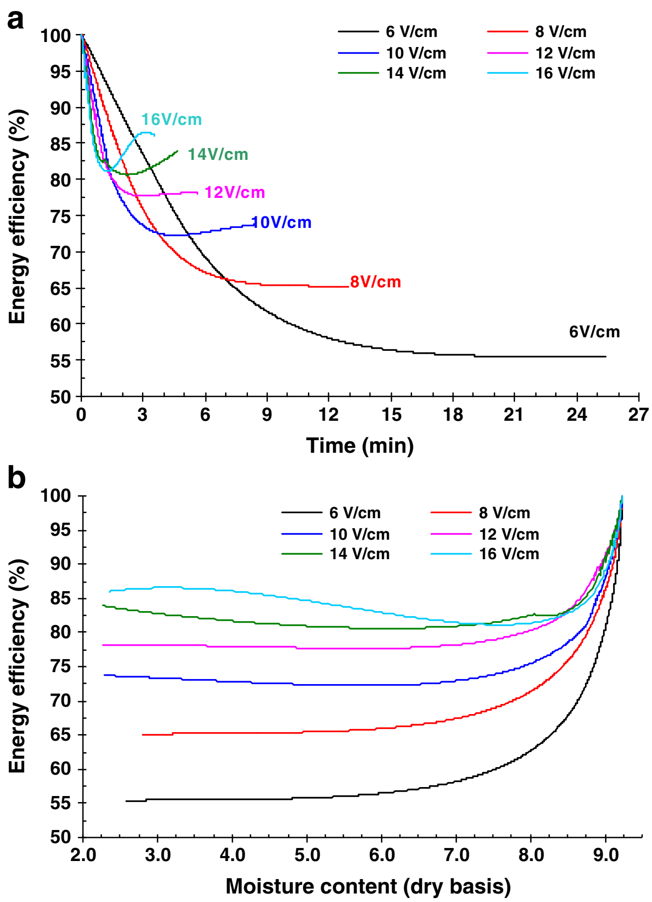

Fig. 5. Variation of energy efficiency with (a) time, (b) moisture content.

2005). The results indicated, as the voltage gradient increased, the heating times to reach the prescribed temperature decreased. This finding is similar to results of several researches (Darvishi et al., 2013; Hosainpour et al., 2014; Icier & Ilicali, 2005a,2005b).

3.2. Energy analysis

Fig. 5 shows the variation of energy efficiency as a function of heating time and moisture content for different voltage gradients. The moisture content and voltage gradient had a significant effect on the energy efficiency of ohmic system ($P < 0.05$). The energy efficiency was found to be high at the initial stage of the heating process, but it decreased during the heating with moisture content, and then remained constant until the end of the heating process. The stable energy efficiency was greater for tomato samples heated at a higher voltage gradient due to a shorter period of process (Fig. 5). Apparently, during the initial heating phase, all applied electrical energy was used to raise the sample temperature and very little moisture was evaporated. Table 1 presents

Table 2
energy consumed to sensible and evaporation (latent) periods for ohmic heating of tomato samples.

∇V (V/cm)	Sensible (kW)	Evaporation (latent, kW)	Total (kW)
6	12.25	61.72	73.97
8	9.36	43.79	53.15
10	8.78	46.08	54.86
12	7.85	44.26	52.11
14	7.37	43.72	51.09
16	7.11	37.40	44.51

the maximum, minimum and average values of the energy analysis of this process. The energy efficiency of ohmic system for different gradients of 6, 8, 10, 12, 14, 16 V/cm were 55.53–99.30%, 65.07–99.91%, 72.24–99.74%, 77.68–99.62%, 80.61–100%, and 81.14–100%, respectively.

It is evident from Table 1 that as voltage gradient was increased from 6 to 16 V/cm, the average energy efficiency increased from 67.07% to 85.50 ($P < 0.05$). This was because of the dramatic reduction in the drying time with an increase in voltage gradient. Icier (2003) reported that the energy efficiency of ohmic system for the liquid samples were in the range of 47–92% during ohmic heating. The conventional method of processing results in low overall efficiency, approximately 30–50% (Iguaz, Lopez, & Virseda, 2002; Tippayawong, Tantakitti, & Thavornun, 2008). In other words, around 50–70% of energy input is wasted. This highly energy- intensive process consumes enormous quantities of fossil fuels. Nargesi (2011) reported that the energy efficiency of ohmic method was significantly higher than that of the conventional process ($P < 0.05$).

Table 2 shows the average values of energy consumed to sensible and evaporation (latent) periods of ohmic heating at different voltage gradients. According to the results, approximately 14–17% of the total energy input is consumed in order to increase product temperature (sensible heat). However, the sensible heat increased with decreasing voltage gradient. Also, the energy needed for evaporation varied from 37.40 to 61.72 kW over the voltage gradient range (Table 2).

Results showed that energy loss increased with decreasing moisture content and voltage gradient (Fig. 6; $P < 0.05$). The reduction of efficiency was more obvious with a low-voltage gradient. Average energy losses of ohmic system were found to vary from 6.88 to 21.48 kW depending on the heating voltage gradient (Table 1).

The maximum temperature of test cell and electrodes was between 68.70 and 76.20 °C. The heat required to heat up the components cell was estimated to be 13.1–43.0% (2.81–2.69 kW) of the average energy loss of ohmic system. The energy losses to the surrounding by natural convection during ohmic heating were 11.3–12.4% (0.78–2.66 kW) of the average energy loss, and it could be reduced by using insulation wall of ohmic cell. Therefore, the energy losses from physical, chemical and electrochemical changes during ohmic process were varied in the range of 3.73 kW (45.57% of average energy loss) for 16 V/cm to 5.47 kW (75.4% of average energy loss) for 6 V/cm. Assiry et al. (2003) reported that the energy losses can be mostly explained by the energies used for the purposes of physical, chemical and electrochemical changes during heating. It is clear that such energy loss was reduced with increase of the voltage gradient. This behavior was probably due to

Table 1
Results of energy and exergy analysis.

∇V (V/cm)	η_{en} (%)		E_{loss}(kW)		η_{ex} (%)		EX_{loss}(kW)	
	min-max	mean	min-max	mean	min-max	mean	min-max	mean
6	55.53–99.30	67.07	0.02–37.30	21.48	3.00–49.30	27.75	0.02–37.28	21.47
8	65.07–99.91	73.95	0.02–24.70	14.91	3.55–58.71	36.38	0.04–24.67	14.90
10	72.24–99.74	78.07	0.07–16.69	11.64	7.89–69.43	43.10	0.07–16.65	11.61
12	77.68–99.62	82.10	0.11–13.14	8.95	13.59–74.31	50.71	0.10–13.08	8.90
14	80.61–100	84.04	0.00.9.91	7.66	16.10–80.90	54.05	0.12.9.80	7.60
16	81.14–100	85.40	0.00–8.69	6.88	9.77–83.51	60.34	0.14–8.81	6.81

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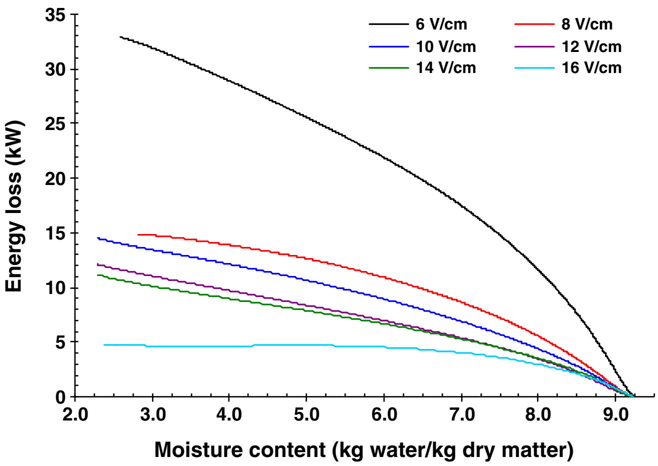

Fig. 6. Variation of energy loss with moisture content.

the residence time of different reactions such as hydrolysis of the tomato samples and corrosion of electrodes that might occur during the ohmic heating. The decrease in the treatment times and increases the water evaporation rates due to higher voltage gradient provided the minimization of electro-chemical reactions, which indicated the decrease in the energy loss of the system. These results were similar to the results in the literature (Assiry et al., 2010; Darvishi et al., 2013; Torkian, Borghei, Beheshti, & Hosseini, 2015).

Fig. 7 shows average values of specific energy consumption for ohmic heating of tomato samples. The values changed between 4.64 MJ/kg water (1.29 kWh/kg of water evaporation) and 2.73 MJ/kg water (0.76 kWh/kg of water evaporation). Specific energy requirement decreased with increasing voltage gradient ($P < 0.05$). The energy consumption obtained in the heating process using 16 V/cm was 1.70-fold lower than 6 V/cm voltage gradient levels. One reason may be that the heating time was longer under a lower voltage gradient and resulted in an increase in energy consumption. Similar results were reported by Hosainpour et al. (2014); Darvishi et al. (2013) and Bozkurt and Icier (2010). Specific energy consumption was correlated as follows:

$$E_{sc} = 0.0208\ \nabla V^2 - 0.6444 \nabla V + 7.7289\ R^2 = 0.9944 \tag{21}$$

3.3. Electrical conductivity

The dielectric properties of the product being heated are proportionally related to moisture content (Soysal, Oztekin, & Eren, 2006). The variations of energy efficiency can be explained by the electrical conductivity of the sample during ohmic heating process. This is due to the fact that the rates of ohmic heating and mass transfer depended on the electrical conductivity. The energy generation is directly proportional to the square of the electric field strength and the electrical conductivity (Marra et al., 2009; Sarang et al., 2008).

$$E_s = \sigma\, \nabla V^2 \tag{22}$$

The changes in the electrical energy input and current intensity with moisture content are given in Fig. 8. During the initial period of heating, warming up, current intensity increased until boiling point, and then showed a sudden reduction at the beginning of evaporation rate process. It was also noted that an increase in the voltage gradient from 6 to 12 V/cm resulted in a significant increase of current intensity at same moisture content ($P \le 0.05$). Therefore, the electrical energy input was greater for tomatoes heated at a lower voltage gradient than those heated at a higher voltage gradient for the same average moisture content of the samples ($P \le 0.05$).

Electrical conductivity – moisture content curves for tomato samples are shown in Fig. 9. Statistical analyses showed that the moisture content had more effect on the electrical conductivity than the temperature especially at high concentrations (low moisture content). It should be noticed that there was no insignificant effect of the voltage gradient on the electrical conductivity (Fig. 9). The low electrical field strength in the range of 3.3–13.3 (V/cm) in a food material containing 3–4% NaCl salts did not affect electrical conductivity (Assiry et al., 2010). It was apparent that electrical conductivity rapidly increased during the warm-up period, when the samples approached the boiling point (≥93 °C), the electrical conductivity was reduced due to the formation of vapor which worked as an electrical insulation. After the bubbling process, a steady rise in the electrical conductivity (nonlinear form – third order polynomial) was observed as the evaporation water was increased in all samples. Similar relative increase in the electrical conductivity with temperature was observed on foodstuffs (Assiry et al., 2010; Darvishi et al., 2013; Icier, Yildiz, & Baysal, 2008; Sarang et al., 2008). Due to reduced drag for the movement of ions, electrical conductivity increased with temperature (Icier & Ilicali, 2005a; Icier et al., 2008). Icier and Ilicali (2005a) and Darvishi et al. (2013) reported that when water is boiling, gas bubbles are formed. This phenomenon appears due to localized high current densities of various oxidation/reduction reactions (e.g. H_2 or O_2 gas). It is clear from Fig. 9 that the electrical conductivity decreased with increase of the voltage gradient which could be due to the decreasing rates of vapor formation and temperature at lower voltage gradient. The results were generally in agreement with some of the literature on the ohmic heating of various food products (Castro et al., 2004; Darvishi, Zarein, Minaie, & Khafajeh, 2014;

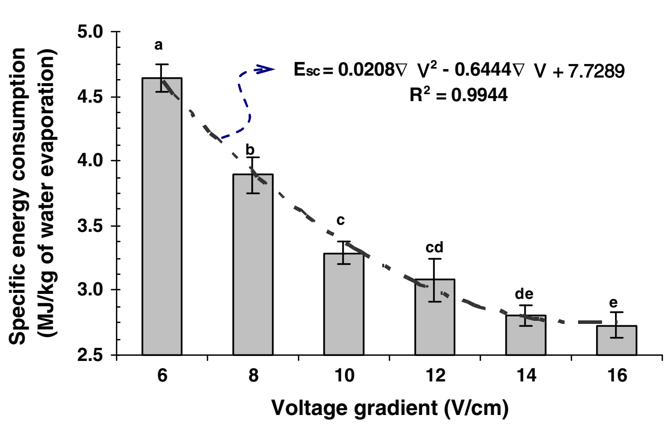

Fig. 7. Amount of specific energy required for ohmic heating of tomato samples. [a–e] Different superscripts in the same column indicate significant differences ($P < 0.05$).

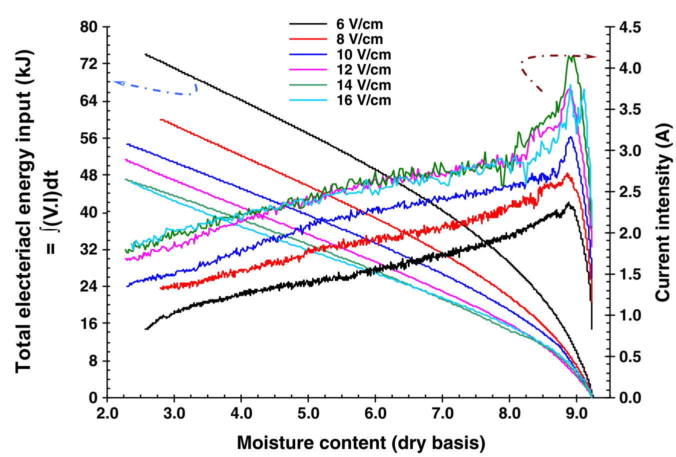

Fig. 8. Variation of electrical energy input and current intensity at different voltage gradients.

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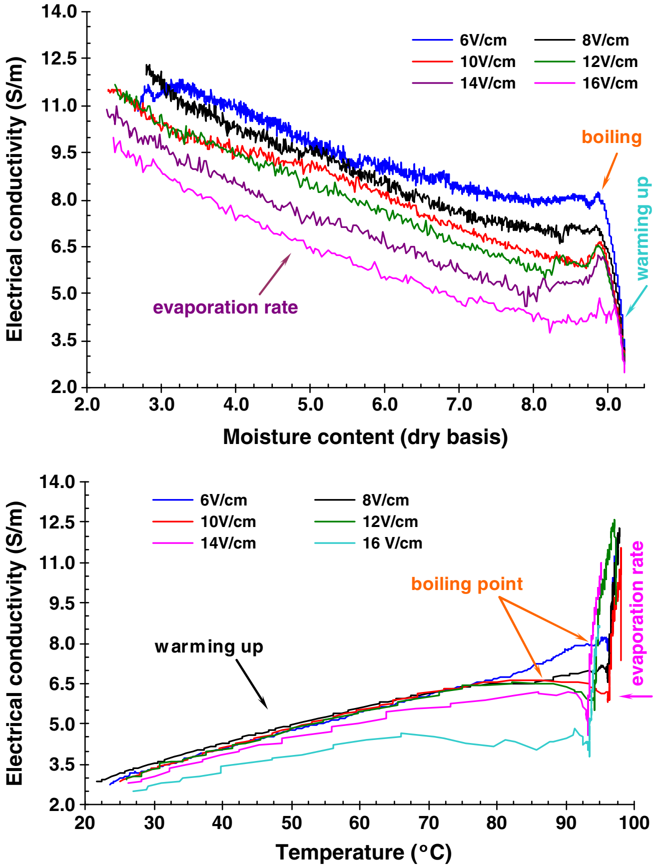

Fig. 9. Electrical conductivity changes of the tomato samples during ohmic heating.

Darvishi et al., 2013; Icier et al., 2008; Sarang et al., 2008). It is also noted that increasing the voltage gradient from 6 to 16 V/cm led to a decrease in the electrical conductivity which could be due to the increasing rates of vapor formation at higher voltage gradient. This finding is similar to the results of several publications (Assiry, 2011; Assiry et al., 2010; Torkian et al., 2015).

The electrical conductivity values of tomato samples at gradient voltage level of 6–16 V/cm were varied in the range of 2.36–12.38 S/m. The resulting values of electrical conductivity are comparable to those of some agricultural products that have been estimated by different authors as shown in Table 3. Zell, Lyng, Morgan, Cronin, and Morgan (2009) found that when the electrical conductivity of product was higher (>2.5 S/m), it included salts such as sodium chloride, sodium nitrate and the formulations containing these salts. Higher electrical conductivity of tomato sample may be attributed to the higher ionic mobility in comparison to juices and fruits such as potato, lemon, apple, orange and sour cherry juices, apricot and peach puree.

Table 3
Electrical conductivity of some agricultural products.

Products	Electrical conductivity (S/m)	References
Corn starch	1.52–3.2[a]	Wang (1995)
Tomato juice	3.22–9.18[a]	Torkian et al. (2015)
Potato	1.2–4.3[a]	Marra et al. (2009)
Carrot	2–4.5	Choi, Nguyen, Lee, and Jun (2011)
lemon juice	0.4–1.0[b]	Darvishi, Hosainpour, Nargesi, Khoshtaghza, and Torang (2011)
Orange juice	0.15–1.15[b]	Icier and Ilicali (2005a)
Tomato juice	0.2–2.75[b]	Srivastav and Roy (2014)
Tomato soup	1.5–4.2	Somavat, Hussein, Chung, Yousef, & Sastry (2012)
Apple and sour cherry juice	0.1–1.6[b]	Icier and Ilicali (2004)
Commercial ham	2–7[a]	Zhu et al. (2010)

[a]For cooking or concentration process.
[b]For pasteurization process.

3.4. Exergy analyses

Exergy efficiency is a valuable tool for identifying the key losses from the system and for optimizing the performance of industrial systems. The variations of exergy efficiency with time and moisture content are given in Fig. 10. As can be seen in Fig. 10, exergy efficiency increased ($P \le 0.05$) with increasing time and decreasing moisture content. This trend was adverse the trend of energy efficiency. This was due to the fact that electrical energy input at beginning heating process was used in raising the sample temperature and very little moisture was evaporated that lead to lower exergy efficiency values. As drying proceeds, evaporation rates increased and thus resulted in increasing exergy efficiency. The exergetic efficiencies varied between 3.0–49.30% at 6 V/cm, 3.55–58.71% at 8 V/cm, 7.89–69.43% at 10 V/cm, 13.59–74.31% at 12 V/cm, 16.10–80.90% at 14 V/cm, and 9.77–83.51% at 16 V/cm. It can be observed that increasing voltage gradient substantially increases the evaporation rate and consequently an increase of exergy efficiency was observed ($P \le 0.05$). This indicates that water evaporation rate within the sample was quicker during higher voltage gradient heating because the current passing through the sample was higher and this increased the heat generation rate.

The results of exergy analyses are summarized in Table 1. The average values of exergy efficiency for ohmic processing of tomato samples for the conditions studied were found to range between 27.75–60.34% (Table 1) while the energy efficiency was higher for the same conditions ($P \le 0.05$). These results were similar to the results of others (Akpinar et al., 2006; Bozkurt, 2009; Bozkurt & Icier, 2010; Corzo,

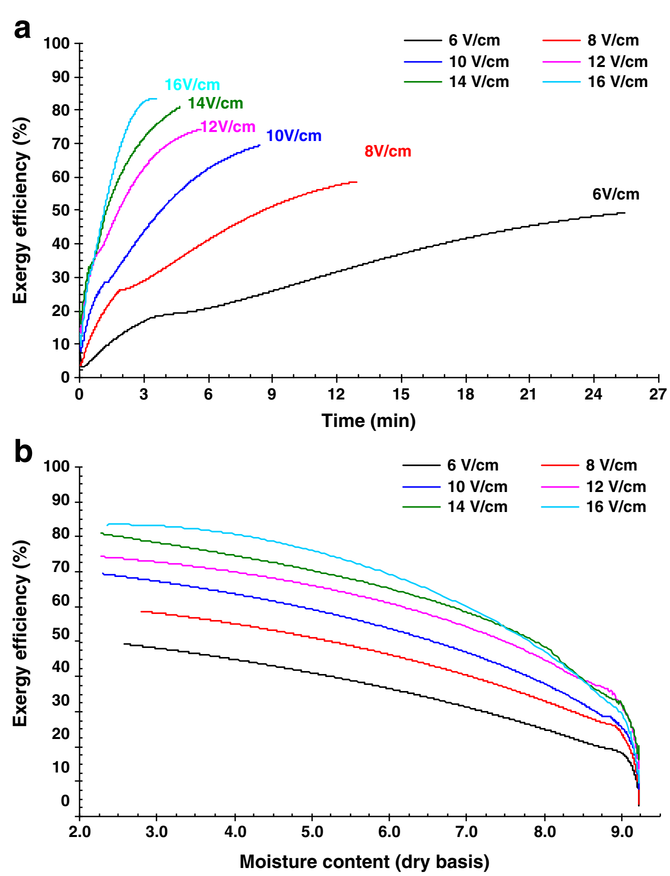

Fig. 10. Variation of exergy efficiency as a function of (a) time, (b) moisture content.

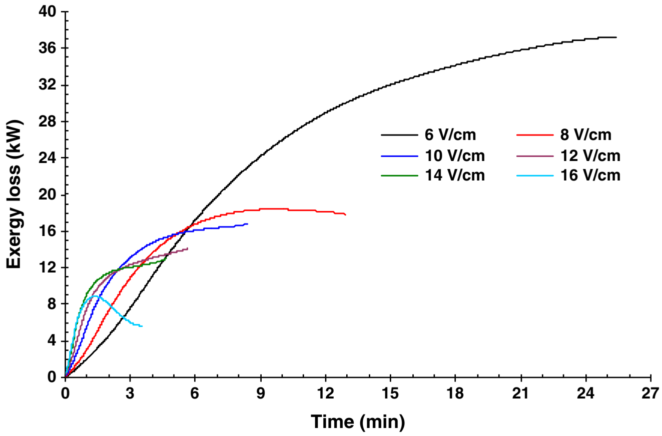

Fig. 11. Influence of voltage gradient on the exergy loss of tomato heating.

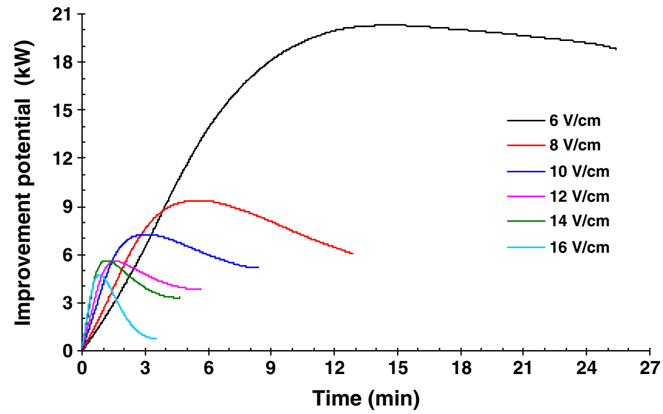

Fig. 13. Variation of improvement potential of tomato samples during ohmic heating.

Bracho, Vasquez, & Pereira, 2008; Darvishi et al., 2014; Erbay & Icier, 2010). Also, the average values of η_{ex} increased progressively as the voltage gradient increased ($P \le 0.05$). A similar trend has been observed by Bozkurt and Icier (2010) in ohmic cooking process of beef. They concluded that the decrease in the treatment times and more homogeneous heating provided the minimization of energy losses or equivalently entropy generation, which meant the increase in the exergetic efficiency of the system. It was obtained that the application of the higher voltage gradient (16 V/cm) was needed to increase exergetic efficiency of ohmic heating. The average exergy efficiency was estimated for heating condition as shown in Eq. (23):

$$(\eta_{ex})_{ave} = -0.275\nabla V^2 + 9.0413\nabla V - 13.249 \quad R^2 = 0.995 \tag{23}$$

Fig. 11 shows the exergy loss versus heating time of the tomato samples at voltage gradients.

The value of exergy loss increased ($P \le 0.05$) with increasing heating time. An analysis of variance showed that the exergy loss increased ($P \le 0.05$) with the decrease in voltage gradient and a decrease in moisture content. The mean values of exergy loss for 6, 8, 10, 12, 14 and 16 V/cm were obtained 21.47, 14.90, 11.61, 8.90, 7.60, and 6.81 kW, respectively (Table 1). Maximum and minimum values of exergy loss were obtained with a voltage gradient of 6 and 16 V/cm, respectively. Aghbashlo, Kianmehr, and Arabhosseini (2009) and Corzo et al. (2008) reported that the exergy loss occurs where the temperature boundary of the heating system is higher than the ambient temperature. Thus, prevention of heat transfer across the boundary of the system could reduce the exergy loss. This could be approached by isolating the ohmic cell, designing and selecting appropriate components and choosing the optimum heating conditions.

Fig. 12 shows the variations of the energy and exergy as a function of electrical conductivity for each heating gradient voltage. It can be observed from these figures that there is an opposite trend the energy efficiency – electrical conductivity with exergy efficiency – electrical conductivity. During initial heating process, energy efficiency decreased with an increasing of electrical conductivity of tomato samples while exergy efficiency increased. At the beginning of the boiling process, energy efficiency intensively decreased (with slope ≈90°) and then nearly fixed with increasing electrical conductivity, while exergy efficiency significantly increased with electrical conductivity ($P \le 0.05$).

Fig. 13 shows the changes of improvement potential with time at different voltage gradient levels. The improvement potential rapidly increased and then slowly decreased with increasing heating time or reduction of moisture content. As it was expected, when the voltage gradient was increased, the exergy loss decreased (Fig. 11), and the improvement potential decreased. The average values of improvement potential are presented in Fig. 14. It was noted that improvement potential values (14.18–2.82 kW) decreased greatly with increasing voltage gradient ($P \le 0.05$). Similar findings were reported by Bozkurt and Icier (2010). A linear regression analysis of the average improvement potential with a voltage gradient resulted in following relationship:

$$IP_{ave} = 0.1489\nabla V^2 - 4.353\nabla V + 34.596 \quad R^2 = 0.9926 \tag{24}$$

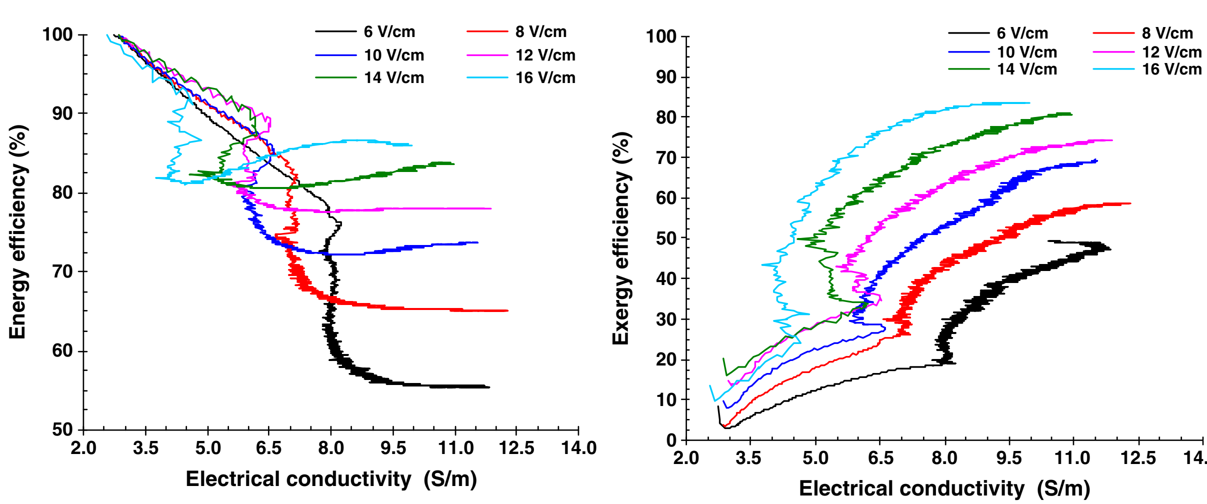

Fig. 12. Variations of energy and exergy efficiencies with electrical conductivity.

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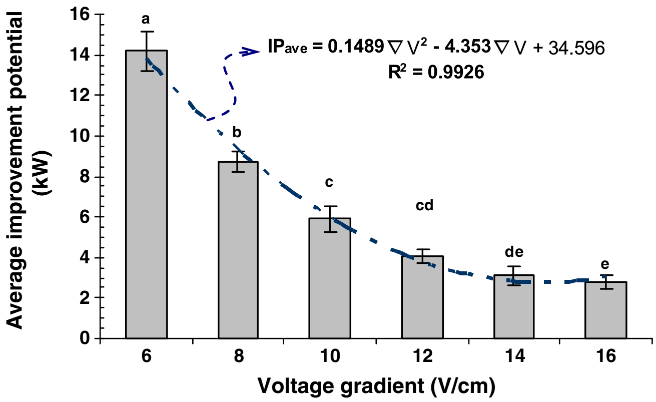

Fig. 14. Average improvement potential at different voltage gradients. [a–e] Different superscripts in the same column indicate significant differences ($p < 0.05$).

4. Conclusion

It is necessary to show the variations of energy and exergy with time in order to determine when and where the maximum and minimum values of the energy or exergy losses took place during the ohmic heating process. This paper deals with the performance evaluation of ohmic heating process of liquid food by applying exergy analysis. The results showed that the energy efficiency decreased at all voltage gradients with decrease in moisture content, while the opposite trend is observed for exergy efficiency (exergy efficiency increase with decrease in moisture content). Also, the average values of energy efficiency (67.07–85.50%) are higher than that exergetic efficiency of system (31.77–60.34%). The electrical conductivity of tomato samples (2.36–12.38 S/m) increased with a reduction of moisture content. The values of specific energy consumption varied from of 4.64–2.73 MJ/kg of water evaporation. The average values of improvement potential and exergy loss between 2.82–14.18 kW and 6.81–21.47 kW, respectively. The most exergy losses took place for the 6 V/cm voltage gradients.

References

Abdelmotaleb, A., El-Kholy, M.M., Abou-El-Hana, H., & Younis, M.A. (2009). Thin layer drying garlic slices using convection and (convection-infrared) heating modes. *Journal of Agricultural Engineering Research*, *29*(1), 251-181.

Aghbashlo, M., Kianmehr, M.H., & Arabhosseini, A. (2009). Performance analysis of drying of carrot slices in a semi-industrial continuous band dryer. *Journal of Food Engineering*, *91*, 99–108.

Aghbashlo, M., Mobli, H., Rafiee, S., & Madadlou, A. (2013). A review on exergy analysis of drying processes and systems. *Renewable and Sustainable Energy Reviews*, *22*, 1–22.

Akpinar, E.K., Midilli, A., & Bicer, Y. (2006). The first and second law analyses of thermodynamic of pumpkin drying process. *Journal of Food Engineering*, *72*, 320–331.

Allali, H., Marchal, L., & Vorobiev, E. (2010). Blanching of strawberries by ohmic heating: effects on the kinetics of mass transfer during osmotic dehydration. *Food and Bioprocess Technology*, *3*, 406–410.

Assiry, A.M. (2011). Application of ohmic heating technique to approach near-ZLD during the evaporation process of seawater. *Desalination*, *280*, 217–223.

Assiry, A.M., Galiy, M.H., Alsamee, M., & Sarifudin, A. (2010). Electrical conductivity of seawater during ohmic heating. *Desalination*, *260*, 9–17.

Assiry, A., Sastry, S.K., & Samaranayake, C. (2003). Degradation kinetics of ascorbic acid during ohmic heating with stainless steel electrodes. *Journal of Applied Electrochemistry*, *33*(2), 187–196.

Bozkurt, H. (2009). *The application, mathematical modelling and exergetic optimization of ohmic cooking in kofte production.* M.sc. Thesis Izmir: Ege University, 262 (in Turkish).

Bozkurt, H., & Icier, F. (2009). *Optimization of ohmic cooking of grounded beef-fat blends: exergy approach.* Bio and Electro-technologies, 21–23 October, Compeigne, France.

Bozkurt, H., & Icier, F. (2010). Exergetic performance analysis of ohmic cooking process. *Journal of Food Engineering*, *100*, 688–695.

Castro, I., Teixeira, J.A., Salengke, S., Sastry, S.K., & Vicente, A.A. (2004). Ohmic heating of strawberry products: electrical conductivity measurements and ascorbic acid degradation kinetics. *Innovative Food Science & Emerging Technologies*, *5*, 27–36.

Celma, A.R., Cuadros, F., & Rodriguez, F. (2012). Convective drying characteristics of sludge from treatment plants in tomato processing industries. *Food and Bioproducts Processing*, *90*, 224–234.

Chen, C., Abdelrahim, K., & Beckerich, I. (2010). Sensitivity analysis of continuous ohmic heating process for multiphase foods. *Journal of Food Engineering*, *98*, 257–265.

Choi, W., Nguyen, L.T., Lee, S.H., & Jun, S. (2011). A microwave and ohmic combination heater for uniform heating of liquid–particle food mixtures. *Journal of Food Science*, *76*, 576–585.

Chowdhury, M.M.I., Bala, B.K., & Haque, M.A. (2011). Energy and exergy analysis of the solar drying of jackfruit leather. *Biosystems Engineering*, *110*, 222–229.

Corzo, O., Bracho, N., Vasquez, A., & Pereira, A. (2008). Energy and exergy analyses of thin layer drying of coroba slices. *Journal of Food Engineering*, *86*, 151–161.

Darvishi, H., Hosainpour, A., Nargesi, F., Khoshtaghza, M.H., & Torang, H. (2011). Ohmic processing: temperature dependent electrical conductivities of lemon juice. *Modern Applied Science*, *5*(1), 210–216.

Darvishi, H., Khoshtaghaza, M.H., & Najafi, G. (2013). Ohmic heating of pomegranate juice: Electrical conductivity and pH change. *Journal of the Saudi Society of Agricultural Sciences*, *12*, 101–108.

Darvishi, H., Zarein, M., Minaie, S., & Khafajeh, H. (2014). Exergy and energy analyses, drying kinetics and mathematical modeling of white mulberry drying process. *International Journal of Food Engineering*, *10*, 269–280.

Erbay, Z., & Icier, F. (2010). A review of thin layer drying of foods: theory, modeling, and experimental results. *Critical Reviews in Food Science and Nutrition*, *50*, 441–464.

Goullieux, A., & Pain, J.P. (2005). In D.W. Sun (Ed.), *Emerging technologies for food processing* (pp. 469–505). London, UK: Elsevier Academic Press.

Hall, C.W. (1975). *Drying farm crops.* Mich: Edwards Bros. Inc.

Hammond, G.P., & Stapleton, A.J. (2001). Exergy analysis of the United Kingdom energy system. *Proceedings of the Institution of Mechanical Engineers*, *215*(2), 141–162.

Heldman, D.R. (2003). *Encyclopedia of agricultural, food, and biological engineering.* New York: Marcel Dekker Inc., Sof edition.

Hosainpour, A., Nargesi, F., Darvishi, H., & Fadavi, A. (2014). Ohmic pre-drying of tomato paste. *Food Science and Technology International*, *20*, 193–204.

Icier, F. (2003). The Experimental Investigation and Mathematical Modeling of Ohmic Heating of Goods. *PhD Thesis, Ege University Institute of Natural and Applied Sciences, Food Engineering Section*, *245* electronic press in www.tez2.yok.gov.tr (No: 134687), in Turkish.

Icier, F., & Ilicali, C. (2004). Electrical conductivity of apple and sour cherry juice concentrates during ohmic heating. *Journal of Food Process Engineering*, *27*, 159–180.

Icier, F., & Ilicali, C. (2005a). The Effects of concentration on electrical conductivity of orange juice concentrates during ohmic heating. *European Food Research and Technology*, *220*, 406–414.

Icier, F., & Ilicali, C. (2005b). The Use of tylose as a food analog in ohmic heating studies. *Journal of Food Engineering*, *69*, 67–77.

Icier, F., Yildiz, H., & Baysal, T. (2008). Polyphenoloxidase deactivation kinetics during ohmic heating of grape juice. *Journal of Food Engineering*, *85*, 410–417.

Iguaz, A., Lopez, A., & Virseda, P. (2002). Influence of air recycling on the performance of a continuous rotary dryer for vegetable wholesale by-products. *Journal of Food Engineering*, *54*, 289–297.

Lebovka, N.I., Shynkaryk, M.V., & Vorobiev, E. (2006). Drying of potato tissue pretreated by ohmic heating. *Drying Technology*, *24*, 601–608.

Liu, Z., Jayasingh, S., Gao, W., & Farid, M. (2007). Corrosion mechanism of electrodes inohmic cooking. *Asia-Pacific Journal of Chemical Engineering*, *2*, 487–492.

Marra, F., Zell, M., Lyng, J.G., Morgan, D.J., & Cronin, D.A. (2009). Analysis of heat transfer during ohmic processing of a solid food. *Journal of Food Engineering*, *91*, 56–63.

Nargesi, F. (2011). *Determination and checking of energy consumption during batch ohmic and ohmic-convective heating to produce tomato paste.* M.sc. Thesis Ilam, Iram: Ilam University, 137 (in Persian).

Ozkan, N., Ho, I., & Farid, M. (2004). Combined ohmic and plate heating of hamburger patties: quality of cooked patties. *Journal of Food Engineering*, *63*, 141–145.

Prommas, R., Rattanadecho, P., & Jindarat, W. (2012). Energy and exergy analyses in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt system (CMCB). *International Communications in Heat and Mass Transfer*, *39*, 242–250.

Sarang, S., Sastry, S.K., & Knipe, L. (2008). Electrical conductivity of fruits and meats during ohmic heating. *Journal of Food Engineering*, *87*, 351–356.

Sharqawy, M., John, H.L.V., & Syed, M.Z. (2010). The thermo physical properties of seawater: A review of existing correlations and data. *Desalination and Water Treatment*, *16*, 354–380.

Somavat, R., Hussein, M.H.M., Chung, Y.K., Yousef, A.E., & Sastry, S.K. (2012). Accelerated inactivation of *Geobacillus stearothermophilus* spores by ohmic heating. *Journal of Food Engineering*, *108*, 69–76.

Soysal, A., Oztekin, S., & Eren, O. (2006). Microwave drying of parsley: modeling, kinetics, and energy aspects. *Biosystems Engineering*, *93*(4), 403–413.

Srivastav, S., & Roy, S. (2014). Changes in electrical conductivity of liquid foods during ohmic heating. *International Journal of Agricultural and Biological Engineering*, *7*, 133–135.

Stancl, J., & Zitny, R. (2010). Milk fouling at direct ohmic heating. *Journal of Food Engineering*, *99*, 437–444.

Tippayawong, N., Tantakitti, C., & Thavornun, S. (2008). Energy efficiency improvements in longan drying practice. *Energy*, *33*, 1137–1143.

Torkian, M., Borghei, A.M., Beheshti, B., & Hosseini, S.E. (2015). The process of producing tomato paste by ohmic heating method. *Journal of Food Science and Technology*, *52*, 3598–3606.

Torki-Harchegani, M., Ghanbarian, D., & Sadeghi, M. (2014). Estimation of whole lemon mass transfer parameters during hot air drying using different modelling methods. *Heat and Mass Transfer.* http://dx.doi.org/10.1007/s00231-014-1483-1.

Usub, T., Lertsatitthankorn, C., Poomsaad, N., Wiset, L., Siriamornpun, S., & Soponronnarit, S. (2010). Experimental performance of a solar tunnel dryer for drying silkworm pupae. *Food and Bioproducts Processing*, *88*, 149–160.

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Van Gool, W. (1997). Energy policy: fairly tales and factualities. In A. Martins da Cruz, G. Costa Pereira, I.M.R.T. Soares, A.J.P.S. Reis, & O.D.D. Soares (Eds.), *Innovation and technology – strategies and policies* (pp. 93–105). Dordrecht: Kluwer Academic Publishers.

Vikram, V.B., Ramesh, M.N., & Prapulla, S.G. (2005). Thermal degradation kinetics of nutrients in orange juice heated by electromagnetic and conventional methods. *Journal of Food Engineering*, *69*, 31–40.

Wang, W. (1995). *Ohmic heating of foods: physical properties and applications.* Ph.D. dissertation Columbus, OH: The Ohio State University.

Zell, M., Lyng, J.G., Morgan, D.J., Cronin, D.A., & Morgan, D.J. (2009). Ohmic heating of meats: Electrical conductivities of whole meats and processed meat ingredients. *Meat Science*, *83*, 563–570.

Zhong, T., & Lima, M. (2003). The effect of ohmic heating on vacuum drying rate of sweet potato tissue. *Bioresource Technology*, *87*(3), 215–220.

Zhu, S.M., Zareifard, M.R., Chen, C.R., Marcotte, M., & Grabowski, S. (2010). Electrical conductivity of particle–fluid mixtures in ohmic heating: Measurement and simulation. *Food Research International*, *43*, 1666–1672.