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Energy and exergy analyses in microwave drying of orange slices

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Abstract

The orange samples were cut into slices with a thickness of 4 mm and treated with ohmic method for 3, 5, and 7 min as ohmic pre-treatment in three voltages 30, 50 and 70 V. Then, they were dried in three replicates using a microwave dryer and at three powers of 90, 360, and 900 W. The statistical analysis results showed that the ohmic time, ohmic voltage and microwave power are significant for the energy and exergy efficiency and specific energy and exergy loss at 1% level. The highest energy and exergy efficiency was observed at 900 W and in the ohmic time of 7 min. The highest energy and exergy efficiency was observed at 59.041% and 47.76%, respectively. The maximum energy loss was seen at 90 W and ohmic time of 3 min. The microwave power, ohmic time and ohmic voltage were statistically significant for all the parameters (energy and exergy) such that with increasing them, the energy and exergy efficiency increased, while the specific exergy and energy loss decreased.

Keywords: Microwave, Orange, Ohmic pre-treatment, Energy and Exergy.

Introduction

Preservation of food through drying is one of the oldest and the most widespread method that can be used to enhance the strength of the food. Food drying is removing the moisture so that the product can be stored for a long time and be protected against deterioration (Min *et al.* 2005). Drying reduces the amount of enzymatic activity and reduces the rate of the chemical reaction. It also increases the shelf life of food, reducing the weight and volume of food in packaging and transportation equipment, and can be controlled and stored in stores using drying.(Azadbakht *et al.* 2018). In fact, drying is a process that requires high energy consumption due to the high latent heat of water evaporation, and in the food industry, this process uses up for 10% of total energy consumption. Therefore, the energy consumed in drying crops is of great importance for industrial use (Azadbakht *et al.* 2017). Microwave drying is one of the important drying methods. Because of the better focus of energy on the product, the removal of moisture is faster and, compared to other methods, it requires only 20 to 35% space compared to other drying methods (Sharma and Prasad 2006; Wray and Ramaswamy 2015). Also, the thermodynamic analysis and especially exergy analysis in thermodynamic analysis have an essential role in the design and evaluation of thermal systems. Exergy thermodynamic analysis describes the maximum useful work produced by equilibrium heat and analyzed for exergy analysis, several points need to be evaluated, which can be useful in the design of dryers. (Dincer 2000; Dincer 2002). Drying fruits and vegetables is one of the most energy-consuming processes and therefore the drying speed should be increased to reduce the drying rate and energy consumption. Crop skin is one of the most important factors in reducing the rate of moisture removal in crops. It acts as a major resistance to moisture transfer from the interior to the surface. Crop pre-treatment is an important step in the drying process for crops that have been reported to be able to accelerate drying speed by removing wax and forming

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small cracks on the surface of the material to facilitate moisture. (Deshmukh *et al.* 2013).

Ohmic treatment is one of the electron heating methods based on the passage of electrical current through a food product having electrical resistance. The electrical energy is converted to heat while the amount of heat generated through the food product is directly related to the voltage gradient and the electrical conductivity. Ohmic heating as an alternate processing method has shown the potential to yield foods with higher quality compared to conventional heating. This difference is mainly due to its ability to heat materials rapidly and uniformly leading to less aggressive thermal treatment (Nouroallahi Soghani *et al.* 2018).

The use of pretreatment in the drying of products was also reported in the following studies: Darvishi et al. (2014) analyzed the energy and exergy of white mulberries in the process of drying with microwave dryer and reported that the specific energy loss increases with increasing microwave power.

Additionally, energy efficiency was reduced by decreasing the moisture content and microwave power. The best energy and exergy for white mulberry was observed at 100 W microwave power (Hosain Darvishi *et al*, 2014). Salengke et al. (2005) performed an experiment on the effect of ohmic pre-treatment on the drying rate of grapes and adsorption isotherm of raisins, which results from this study reveals that the drying rate of the grapes was significantly increased by the ohmic pre-treatment, especially at low electrical frequencies. The effect of the ohmic pre-treatment on the equilibrium moisture content of the raisins produced was evident at 0.75 or higher water activities but there was no or limited effect at low to moderate water activities (Salengke and Sastry 2005).

Nouroallahi Soghani et al. (2018) Performed an experiment on Ohmic blanching of white mushroom and its pre-treatment during microwave drying Which showed the results of this experiment blanched sample at low voltage and heating duration consumed the minimum total energy during the drying process. According to the drying is one of the important methods of the food industry and is a high energy consumption process, the purpose of this paper was to investigate the effect of ohmic pre-treatment on the energy and exergy value of the microwave dryer. In this investigation, the effect of ohmic voltage and ohmic time on energy and exergy rates were investigated.

Materials and methods

Sample preparation

Freshly harvested oranges (Tamson variety) were purchased from a local store in Gorgan city in Iran and were kept at 10℃ in the laboratory. At the beginning of each experiment, the oranges were washed and the slices were cut in a circular in a thickness of 4 mm and they were weighted. Then, samples were pretreated by ohmic method for 3, 5 and 7 min with 30, 50 and 70 voltage for 30, 60, and 90 min. The drying process was employed in a microwave dryer with 1.2, 4.8, and 12 W/g specific power density in the BioSystem Mechanics Department of Gorgan University of Agricultural Sciences and Natural Resources (Fig. 1). In figure 2, slice changes of samples before and after drying are shown.

Experimental method

Slices were pretreated and placed in containers and dried at three powers of 90, 360, and 900 W. The weight of oranges was measured using a 0.01 mg precision scale. The weight of each sample was measured and recorded at a time interval of 1 min to reach constant moisture. For each treatment, the experiments were repeated in triplicate. Environmental conditions for testing were conducted at a temperature of 20℃ and relative humidity of 71%. First, the oranges were equal to the slices of the same size, then the sample was placed inside the oven and the weight of the sample was measured according to the standards. Then, using Eq. 1, the moisture content was calculated (Yogendrasasidhar and Pydi Setty 2018).

$$MC = \frac{W - W\mathrm{e}}{W} \qquad (1)$$

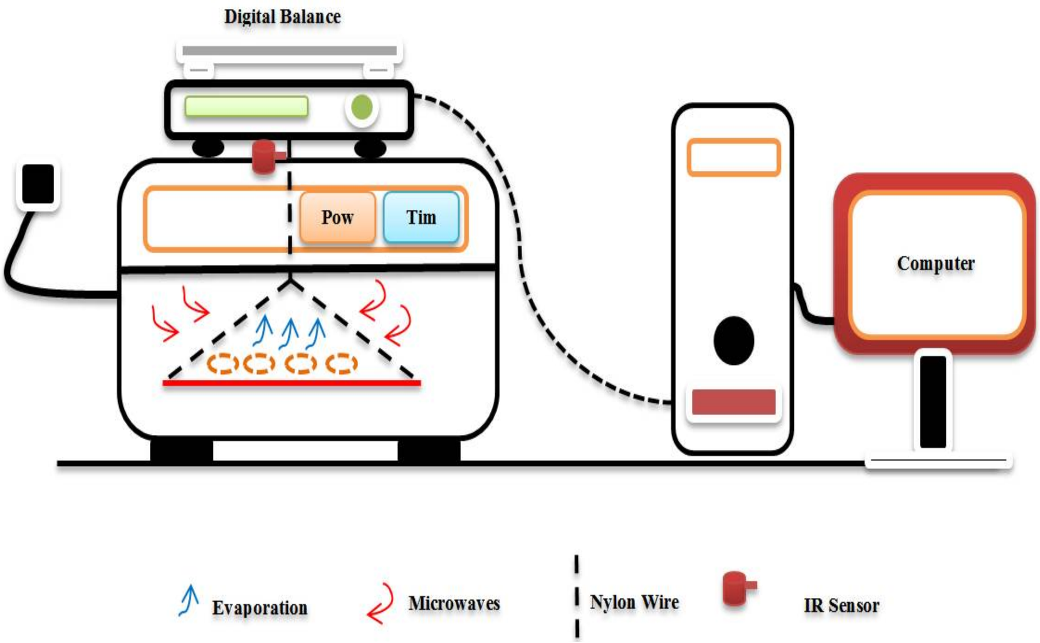

Fig. 1. Diagram of microwave drying system (Azadbakht et al, 2018)

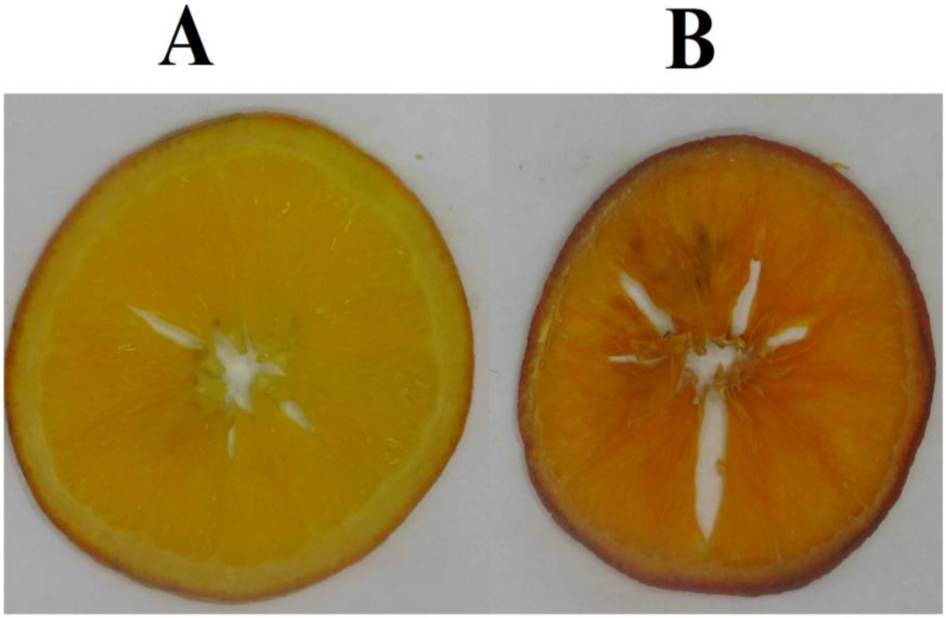

Fig. 2. Orange slice A: Before and B: After drying

Energy analysis

Energy used in the drying and heating process is important for production processes in both industrial and household sectors. However, the price of this energy is extremely expensive; therefore, there is a strong incentive to invent processes that will use energy efficiently. Currently, widely used drying and heating processes are complicated and inefficient and are generally damaging to the environment. Thus, it is required to have a simplified lower-cost approach replicable in a wide range of situations (Jindarat *et al.* 2011).

The mass and energy survival in the microwave dryers' chamber is shown in Fig. 3. The general relation of mass moisture survival is calculated using Eq. (2) (Darvishi *et al.* 2016).

$$\sum m_{in} = \sum m_{out} \qquad (2)$$

According to Eq. 3, the initial mass of the sample is equal to the amount of water vapor removed and the rate of dried sample mass.

$$m_o = m_{ew} + m_p \qquad (3)$$

The mass of evaporated water is obtained using Eq. 4 (Darvishi *et al.* 2014).

$$m_{wt} = m_d(M_0 - M_t) \qquad (4)$$

The protected energy of the sensible heat, latent heat, and the thermal source of the microwave were calculated using Eq. 5 and the input energy of the dryer was calculated using Eq. 6 (Jindarat *et al.* 2011). In Eq. 5, the energy loss is $P_{ref} + P_{tra}$. Eq. 6 shows the input energy of the microwave. This formula is composed of three parts, including absorbed energy, reflected energy, and passed energy. In Eq. 6, $\left((\mathrm{mC_pT})_{\mathrm{dp}} - (\mathrm{mC_pT})_{\mathrm{wp}}\right) + \lambda_K m_{w})$ equals to the absorbed energy of the product.

$$P_{in} = P_{abs} + P_{ref} + P_{tra} \qquad (5)$$

$$\mathrm{P_{in}} \times \mathrm{t} = \left((\mathrm{mC_pT})_{\mathrm{dp}} - (\mathrm{mC_pT})_{\mathrm{wp}}\right) + \lambda_K m_w + E_{ref} + E_{tra} \qquad (6)$$

The latent heat of the orange samples is calculated using Eq. 7 (Abdelmotaleb *et al.* 2009).

$$\frac{\lambda_K}{\lambda_{wf}} = 1 + 23\exp(-40M_t) \qquad (7)$$

The latent heat of free water evaporation was calculated according to using Eq. 8 (Darvishi 2017).

$$\lambda_{wf} = 2503 - 2.386(T - 273) \qquad (8)$$

The thermal capacity is a function of the moisture content and can be calculated through Eq. 9 (Brooker et al. 1992).

$$C_P = 840 + 3350 \times (\frac{M_t}{1 + M_t}) \qquad (9)$$

The thermal efficiency of the dryer is calculated using Eq. 10 (Soysal *et al.* 2006).

$$\eta_{en} = \frac{energy\ absorption}{P_{in} \times t} \qquad (10)$$

The specific energy loss was measured using Eq. 11 (Darvishi *et al.* 2014)

$$E_{loss} = \frac{E_{in} - E_{abs}}{m_w}\ or\ E_{loss} = (1 - \eta_{en}) \times \frac{P_{in} \times t}{m_w} \qquad (11)$$

Exergy analysis

With the onset of the energy crisis, energy and exergy (the maximum useful work that comes from a certain amount of available energy or from the flow of materials) analyses are among the leading thermodynamic research works. In the exergy analysis, the main purpose is to determine the location and amount of irreversible production during the various processes of the thermodynamic cycle and the factors affecting the production of this irreversibility. In this way, in addition to evaluating the performance of various components of the thermodynamic cycle, methods to increase cycle efficiency are also identified (Mokhtarian *et al.* 2016).

The general exergy equilibrium in the microwave chamber is as follows (Darvishi *et al.* 2016).

The amount of exergy transmitted due to evaporation in the drying chamber was calculated using Eq. 14 (Sarker *et al.* 2015)

$$ex'_{exap} = (1 - \frac{T_0}{T_p}) \times m_{wv}\lambda_{wp} \qquad (14)$$

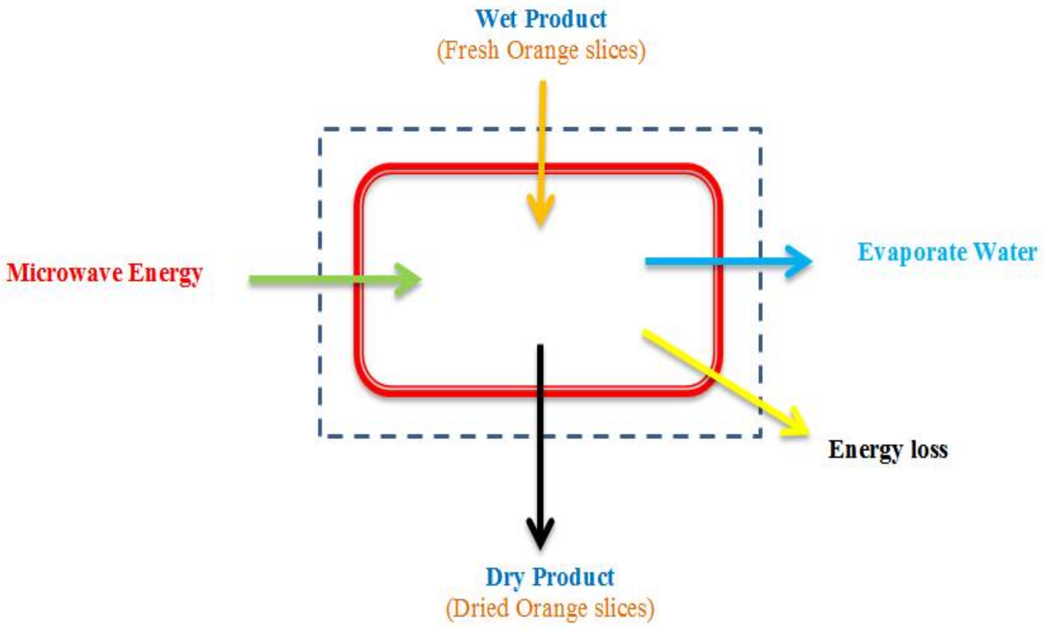

Fig. 3. Volume control of microwave system

$$EX_{in} = EX_{abs} + \underbrace{EX_{ref} + EX_{tra}}_{\text{Exergy loss}} \qquad (12)$$

$$P_{in} \times t = \overbrace{(((m \times ex)_{dp} - (m \times ex)_{wp}) + ex'_{exap} \times t)} + E_{ref} + E_{tra} \qquad (13)$$

where m$_{wv}$ is calculated using Eq. 15 (Darvishi *et al*. 2016).

$$m_{wv} = \frac{m_{t+\Delta t} + m_{wv}\lambda_{wp}}{\Delta t} \qquad (15)$$

Specific exergy loss was calculated using Eq. 16 (Darvishi *et al*. 2014):

$$ex = C_p[(T - T_0) - T_0 \ln(\frac{T}{T_0})] \qquad (16)$$

Exergy efficiency for each dryer system – as the exergy rate used in drying the product to the exergy of drying source supplied to the system is calculated by Eq. 17 (Dincer and Sahin 2004)

$$\eta_{en} = \frac{exergy\ absorption}{P_{in} \times t} \times 100 \qquad (17)$$

The specific exergy loss was calculated using Eq. 18 (H Darvishi 2017).

In this research, the source of temperature and pressure in the environment was set at 20°C and 101.3 MPa, respectively.

$$EX_{loss} = \frac{EX_{in} - EX_{abs}}{m_w} \qquad (18)$$

Statistical analysis

The orange slices were dried in microwave at three powers of 90, 360, and 900, three ohmic times of 3, 5, and 7 min and three voltage 30, 50 and 70 V and the ohmic results were sorted and calculated using the Excel software. All experiments were performed in triplicate and the results were analyzed using a factorial experiment in a completely randomized design with SAS statistical software.

Results and discussion

The analysis of variance (ANOVA) results of orange slices drying in different microwave powers for energy efficiency, specific energy loss, specific exergy loss, and exergy efficiency are shown in Table 1. According to the results, the power of the microwave, voltage and ohmic time were significant for energy efficiency, specific energy loss, specific exergy loss, and exergy efficiency at 1% level. The interaction effect (ohmic time × microwave power) of energy efficiency specific energy loss and exergy efficiency are significant at the 1% level and the interaction voltage × microwave power and voltage × ohmic time non-significance for energy efficiency, specific energy loss, specific exergy loss, and exergy efficiency. Thus, we compared the means with the LSD test.

Table 1. ANOVA results of energy efficiency, specific energy loss, specific exergy loss, and exergy efficiency under different powers and ohmic

Parameter		Energy efficiency		Specific energy loss	
	DF	**Mean Square**	**F Value**	**Mean Square**	**F Value**
Voltage	2	82.517	58.12**	11.07	40**
Ohmic time	2	2293.96	161.60**	190.190	687.09**
Microwave power	2	1987.01	139.42**	6.456	23.32**
Voltage* Ohmic time	4	0.847	0.60	3.749	13.54**
Voltage* Microwave power	4	1.550	1.09	0.763	2.75*
Ohmic time* Microwave power	4	69.186	48.73**	1.142	4.13**
ERROR	80	1.419		0.276	
Parameter		**Exergy efficiency**		**Specific exergy loss**	
	DF	**Mean Square**	**Mean Square**	**Mean Square**	**F Value**
Voltage	2	28.466	14.60	14.60	40**
Ohmic time	2	1385.91	95.76	95.76	687.09**
Microwave power	2	1367.91	70.13	70.13	23.32**
Voltage* Ohmic time	4	0.295	0.247	0.247	13.54**
Voltage* Microwave power	4	0.238	0.239	0.239	2.75*
Ohmic time* Microwave power	4	70.313	0.695	0.695	4.13**
ERROR	80	1.416		0.299	

The effect of power and ohmic time on energy efficiency

Based on Table 1, an interaction effect of microwave power and ohmic time on energy efficiency are significant at the level of 1%. Fig. 4 shows the interaction of these parameters on energy efficiency. According to the results obtained, energy efficiency increased significantly with increasing the power of the microwave and ohmic time. The maximum amount of energy efficiency is observed at the power of 90 W and ohmic time of 7 min (59.041%) and the minimum amount of energy efficiency is observed in a power of 90 W and ohmic time of 3 min (20.096%). Moreover, it can be stated according to the obtained results that the increase in the pretreatment time causes product mass reduction leading to an increase in the dry matter amount and dewatering of the orange slices. Product moisture reduction provides for shorter drying periods that can per se increase the energy output duration. Another reason for such a finding can be realized in orange slices' hardness reduction using ohmic pretreatment and such a reduction in hardness results in the readier de-moisturizing of the orange slices. In addition, the product dewatering takes a faster pace in higher powers and a larger deal of water is seminally forced out of the orange specimens and this causes the shortening of the drying period. In fact, according to the energy formula, it can be stated that the amount of energy absorbed in higher powers exceeds the amount of energy wasted and this makes the energy output be augmented.

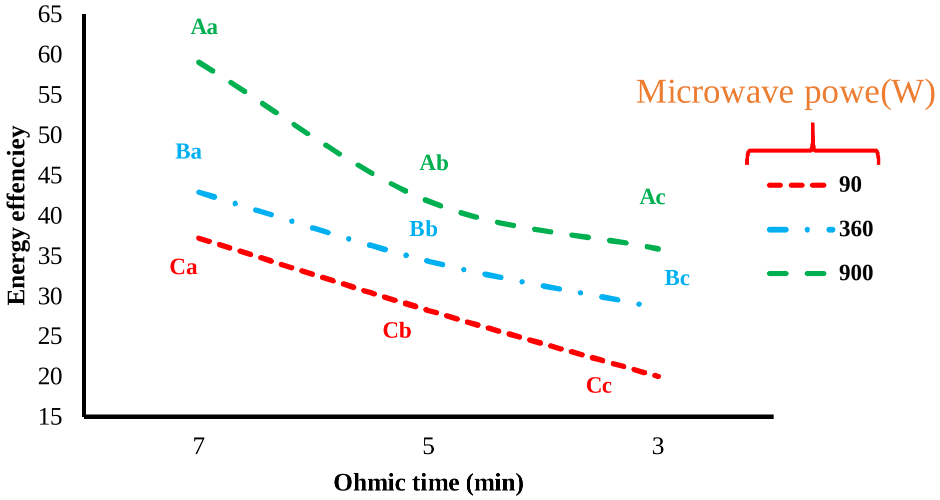

Fig. 4. Interaction of ohmic Pre-treatment and microwave power on energy efficiency
Similar capital letters represent non-significance in a same ohmic time, and similar small letters represent the non-significance in a same power.

According to figure (5), the increase in the voltage rate causes an increase in energy efficiency, as well. The highest energy efficiency was found in 70V and the lowest rate of energy efficiency was documented in 30V. There was evidence a significant difference between the effects of the various measured voltages on energy efficiency. The reason for this can be justified by the fact that increasing the voltage increases the sample temperature and hence the evaporation rate will occur faster and faster in the sample which results in less water after pretreatment, which causes the amount of energy efficiency has increased.

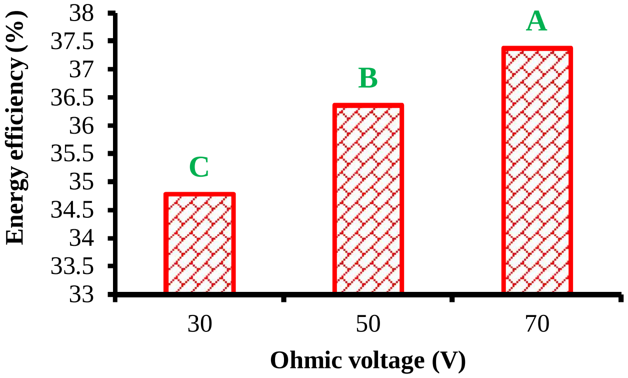

Fig. 5. The effect of ohmic voltage on energy efficiency

The effect of power and ohmic time specific energy loss

Based on Table 1, the power of the microwave was significant at 1% probability level. Fig. 6 shows the results obtained. The maximum amount of the specific energy loss is observed at the power of 90 W and ohmic time of 3 min (7.706 MJ) and the minimum amount of specific energy loss is observed in power of 900 W and ohmic time of 7 min (2.52 MJ). Since there is an inverse relationship between the specific energy loss and the product dewatering, the increase in the amount of water forced out of the product causes a reduction in the amount of specific energy loss. Furthermore, the change in the resistance to the dispersion of the moisture inside the orange slices causes a reduction in the drying time via changing the microstructure thereof subject to physical damage and this ends in a greater reduction in the amount of specific energy loss (Orikasa *et al.* 2018). Also, the voltage increasing caused the energy efficiency increasing, and with this increase, the amount of energy lost in drying decreases, which this reduction had the inverse relation of specific energy efficiency and specific energy loss.

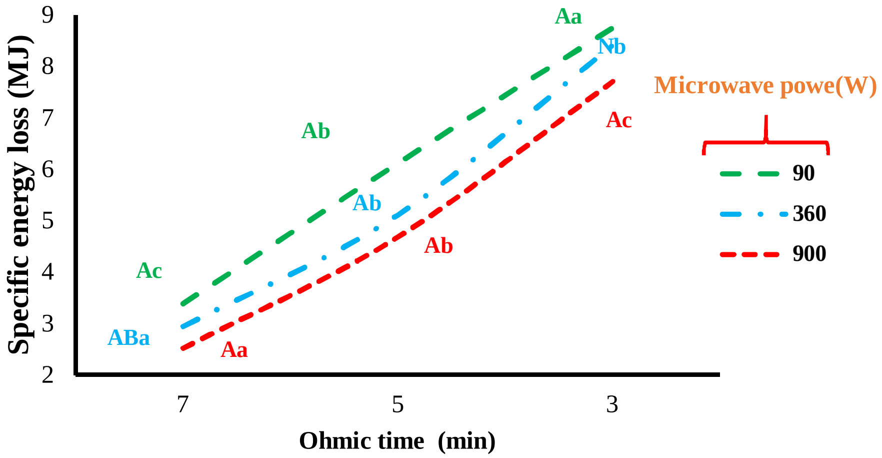

Fig. 6. Interaction of ohmic Pre-treatment and microwave power on specific energy loss
Similar capital letters represent non-significance in a same ohmic time, and similar small letters represent the non-significance in a same power.

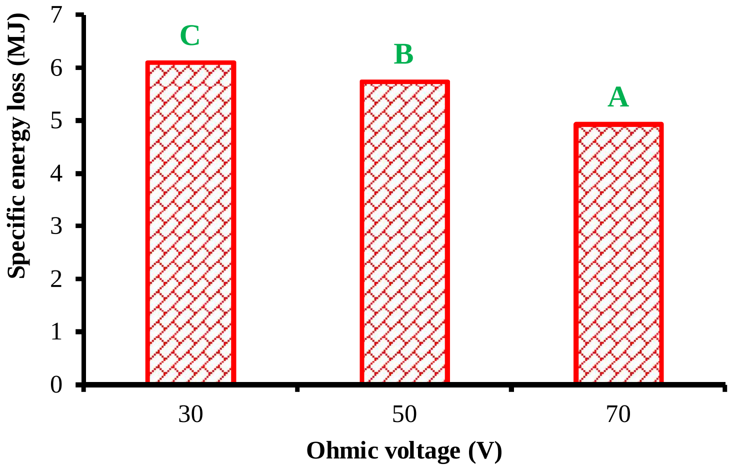

Fig. 7. The effect of ohmic voltage on specific energy loss

The effect of power and ohmic time on exergy efficiency

Figure 8 shows the interaction of these parameters on exergy efficiency. According to the results obtained, exergy efficiency increased significantly with increasing microwave power and ohmic time. The maximum amount of the exergy efficiency was observed at the power of 900 W and 7 min (47.76%) and the minimum amount exergy efficiency is observed in power of 360 W and 3 min (17.55 %). This result can be explained by the fact as power increases, the temperature of the microwave chamber dryer also increases and the product mass is removed faster, leading to reduced orange drying time. This reduction in time and faster mass removal, finally, increases the exergy efficiency of the microwave dryer. For exergy efficiency, useful power is highly important and by reducing drying time, the useful power increases. Moreover, according to Fig. 9, the ohmic time of oranges has a significant effect on the exergy efficiency. Based on this figure, with increasing the ohmic time, the amount of exergy efficiency increased, indicating a better heat exchange at higher ohmic times.

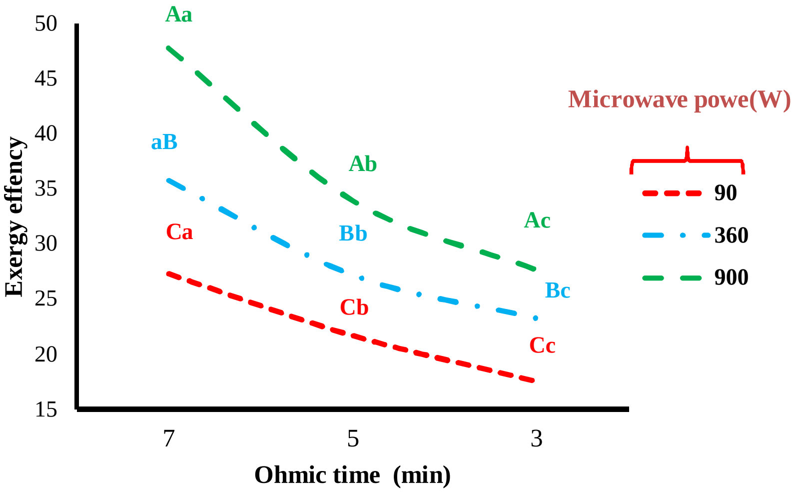

Fig. 8. Interaction of ohmic pre-treatment and microwave power on exergy efficiency
similar capital letters represent non-significance in a same ohmic time, and similar small letters represent the non-significance in a same power.

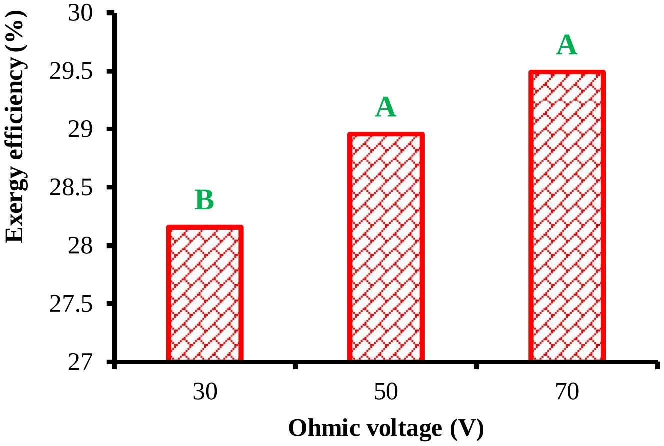

Fig. 9. The effect of ohmic voltage on Exergy efficiency

Effect of microwave power, ohmic time and ohmic voltage on Specific exergy loss

Figure 10 shows the results obtained. The maximum amount of the specific exergy loss is observed at the power of 90 W (11.648 MJ) and the minimum amount of specific exergy loss is observed in power of 900 W (8.421 MJ). Also, according to the figure, there is a significant difference between 90, 360 and 900 W. Also the maximum amount of the specific energy loss in ohmic time is observed at the time of 3 min (8.928 MJ) and the minimum amount of specific energy loss is observed in the time of 7 min (2.93 MJ). The maximum amount of the specific exergy loss is observed at the power of 30 V (10.624 MJ) and the minimum amount of specific exergy loss is observed in the power of 70 V (9.251MJ). The reason for this could be stated as follows that, ohmic pre-treatment has softened the fruit tissue than other pre-treatment methods that this also reduces the drying time and the easier absorption of temperature for the fruit. According to the results for ohmic process time and Specific exergy loss, can be stated that increasing the ohmic process time leads to more moisture removal, which results in faster removal of moisture in the dryer and thus do more and better work on the sample and reduce the amount of Specific exergy loss. On the other hand, increased drying power leads that faster energy being transferred to the sample to raise the temperature, which reduces specific exergy loss.

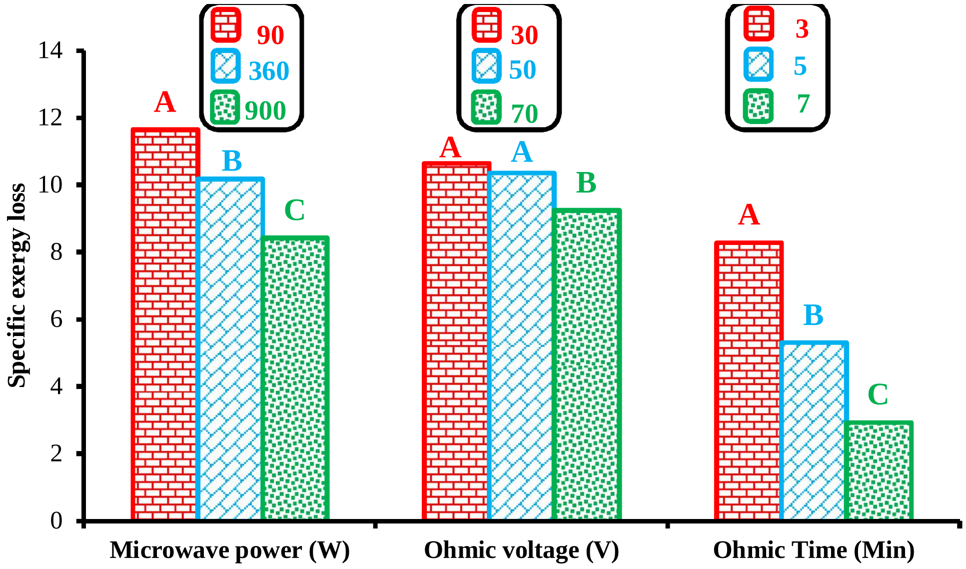

Fig. 10. Effect of microwave power, ohmic time and ohmic voltage on Specific exergy loss

Conclusion

Based on the obtained results, microwave power, ohmic time and ohmic voltage for the energy efficiency, specific energy loss, exergy efficiency and specific exergy loss have had the most significant effects. The interaction of ohmic time and microwave power on the energy efficiency, specific energy loss and exergy efficiency were only found significant. According to the results, the increase in ohmic and voltage time and microwave power brings about an increase in the energy and exergy efficiency and the increase in these factors causes reductions in the specific energy loss and specific exergy loss.

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آنالیز انرژی و اکسرژی در خشک کردن ورقه‌های پرتقال با روش اهمیک

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چکیده

در این تحقیق آنالیز انرژی و اکسرژی در خشک‌کن ماکروویو برای خشک کردن برش‌های پرتقال بررسی شده است که برای این تحقیق ابتدا پرتقال‌ها به‌صورت برش‌های با ضخامت 4 میلی‌متر بریده شده سپس با روش اهمیک در زمان‌های پیش تیمار 3، 5 و 7 دقیقه در ولتاژهای ۳۰،۵۰ و 70 ولت تحت پیش تیمار اهمیک قرار گرفتند. سپس نمونه‌ها در سه تکرار با استفاده از خشک‌کن ماکروویو در سه توان 90، 360 و 900 وات خشک شدند. آنالیزهای آماری نشان داد که زمان اهمیک، ولتاژ اهمیک و توان ماکروویو برای بازده انرژی و اکسرژی و اکسررژی و انرژی تلف شده در سطح آماری 1 درصد معنی‌دار شده است. بیشترین مقدار بازده انرژی و اکسرژی در توان 900 وات و در زمان اهمیک 7 دقیقه مشاهده شد که به‌ترتیب 59/041 و 47/76 درصد بوده است. بیشترین مقدار انرژی تلف شده در توان 90 وات و زمان 3 دقیقه بود. توان ماکروویو، زمان اهمیک و ولتاز اهمیک همگی از لحاظ آماری برای پارامترهای (انرژی و اکسرژی) معنی‌دار بودند و با افزایش مقدار مقدار بازده انرژی و اکسرژی زیاد شد در حالی که انرژی و اکسرژی تلف شده کاهش یافت.

واژه‌های کلیدی: ماکروویو، پرتقال، پیش تیمار اهمیک، انرژی و اکسرژی

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