Shahid Bahonar University of Kerman

Biomechanism and Bioenergy Research

Online ISSN: 2821-1855
Homepage: https://bbr.uk.ac.ir

Iranian Society of Agricultural Machinery Engineering and Mechanization

Investigating the Kinetics, Energy and Exergy of Drying Apple Slices Using Infrared Radiation

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ARTICLE INFO

Article type:

Research Article

Article history:

Received 10 May 2023

Received in revised form 05 June 2023

Accepted 21 June 2023

Available Online 30 June 2023

Keywords:

Drying, Thermodynamic analysis, Modeling, Apples, Infrared radiation.

ABSTRACT

Evaluating energy and exergy can help to optimize the amount of energy consumption in dryers. In this research, apple slices were dried using infrared radiation, and then the energy and exergy of this process were analyzed. For conducting the experiments, apple slices, in two thicknesses of 5 and 10 mm, were prepared and dried using two air mass velocities of 0.006 and 0.012 kg/s and under infrared radiation. The drying time varied from 90 to 130 minutes. Experimental data were fitted to three mathematical models. A logarithmic type model with coefficient determination of 0.99 was the best fit for drying apple slices data. The results of energy and exergy analysis showed that the amount of energy consumption, energy efficiency, the amount of exergy consumed and its efficiency decrease in all treatments. The value of energy efficiency changed between 0.09 and 0.42 and exergy efficiency between 0.01 and 0.81 in different stages indicating that a large amount of energy consumed in dryer, leaves the system unused.

Cite this article: Hosseini, F., Shakiba, R., Rezvani, Z. & Arslan, S. (2023). Investigating the Kinetics, Energy and Exergy Analysis of the Drying Process of Apple Slices Using Infrared Radiation. *Biomechanism and Bioenergy Research*, *2*(1), 1-10. https://doi.org/10.22103/BBR.2023.21678.1043

Publisher: Shahid Bahonar University of Kerman
DOI: https://doi.org/10.22103/BBR.2023.21678.1043

INTRODUCTION

The variety of products and the high consumption of energy in the drying process have led researchers to pay attention to different drying methods to reduce energy consumption. Recently, the drying of food and agricultural products using infrared radiation has attracted the attention of researchers. The energy of infrared radiation reaches the surface of the product without heating the surrounding air, some of it penetrates into the product and causes its temperature to increase and its water to evaporate (Khir et al., 2011). Reduction of drying time, reduction of energy consumption and high quality of dried product are among the advantages of using infrared radiation technology for drying agricultural products. One of the most important influencing factors in infrared dryers is the energy of the infrared lamp, the speed and temperature of the air passing over the product (Afzal & Abe, 1999).

In the study of eggplant drying in a combined dryer of hot air and infrared radiation, the effect of hot air temperature and radiation lamp energy on drying time were investigated. The results showed that by increasing the temperature of the dryer from 60 to 80 degrees Celsius, the drying time decreases from 48 m to 35 m. By increasing the energy of the infrared lamp from 150 to 375 W, the drying time decreased from 35 to 15 m (Salehi et al., 2015). The effect of infrared radiation and bed depth on rice drying were investigated. The results showed that at a constant radiation intensity, the energy consumption decreases with the increase of the depth of the product, and at a constant depth, the energy consumption of the product decreases with the increase of the infrared radiation intensity (Das et al., 2004).

Investigating the thin layer of onion was done by a combined method with air flow and infrared radiation and the effect of lamp energy and temperature and air speed. The results showed that by increasing the power of the lamp at constant temperature and air speed, the drying time decreases. Also, with the increase of air speed in constant lamp power and constant temperature, the drying time increases due to the drying phenomenon of the product surface (Sharma et al., 2005).

One of the methods of energy consumption management in dryers is to study the kinetics of this process in order to produce a good quality product in the shortest possible time with the least energy consumption. In this study, factors such as the speed, temperature and humidity of the incoming air, as well as some product characteristics such as layer thickness, size, and submergence of the product are effective in achieving a good quality dry product with optimal energy consumption. It is the goal of every researcher to obtain the best fitted model. The drying behavior of apple thin layer was investigated in a laboratory dryer. In this process, the effect of air speed was investigated and also by mathematical modeling of the drying process, it was shown that the most suitable model for drying apple layers in this dryer is the logarithmic model (Wang et al., 2007). Thin layers of carrots with a thickness of 0.5 cm were dried at four different temperatures at a speed of 0.5 to 1 m/s using a laboratory dryer. Page's model showed a better result than Henderson and Pabis model (Doymaz, 2004).

In order to reduce energy, thermodynamic analysis of dryers can significantly help to reduce energy consumption. The analysis of energy and exergy of potatoes in a semi-industrial continuous thin layer dryer was investigated. The results showed that exergy losses decrease with increasing product feeding rate, decreasing air flow speed and decreasing temperature. Also, increasing the air flow, temperature and decreasing the feeding rate causes an increase in energy consumption (Aghbashlo et al., 2008). In analyzing the energy and exergy of carrot drying in a fluid bed, the effect of parameters such as particle size, thickness and air velocity was tested. The results of this research showed that by increasing the inlet air temperature, bed thickness and decreasing the particle size, energy consumption increases, and on the other hand, by decreasing the temperature and bed depth and increasing the particle size, exergy losses decrease (Nazghelichi et al., 2010).

Today, drying slices of different fruits such as apples and bananas has become common and dried products have found many customers in the market. Drying these products using infrared radiation can help in maintaining the quality of food and producing dried fruit with better quality.

The main purpose of this research was to investigate the factors affecting the drying of apple slices using infrared waves in a laboratory dryer. In this regard, the kinetics and analysis of energy and exergy of drying apple slices under the influence of different mass velocity of air and different thicknesses were investigated.

MATERIALS AND METHODS

In this research, the variety of golden delicious (Golden delicious) was obtained from the market on a daily basis and after washing and removing surface water, it was cut into two thicknesses of 5 and 10 mm. Then the samples were placed on steel grids to be placed inside the dryer for drying.

The schematic image of the dryer used for this project is shown in Figure. 1. The drying chamber was in the shape of a rectangular cube with dimensions of 80x40x40 cm made of galvanized sheet, which was insulated with a 5 cm layer of glass wool. A drying tray measuring 40 x 40 cm was placed on the load cell to measure the instantaneous mass of the apple. The heat needed for drying was provided by two 250 W infrared lamps. The two air speeds required by the dryer were supplied by a 6 W fan from the bottom of the dryer. The temperature and humidity of the drying air were recorded with electronic sensors at five-minute intervals. In order to reach a stable state of the system, all the tests were started 30 minutes after the system was turned on.

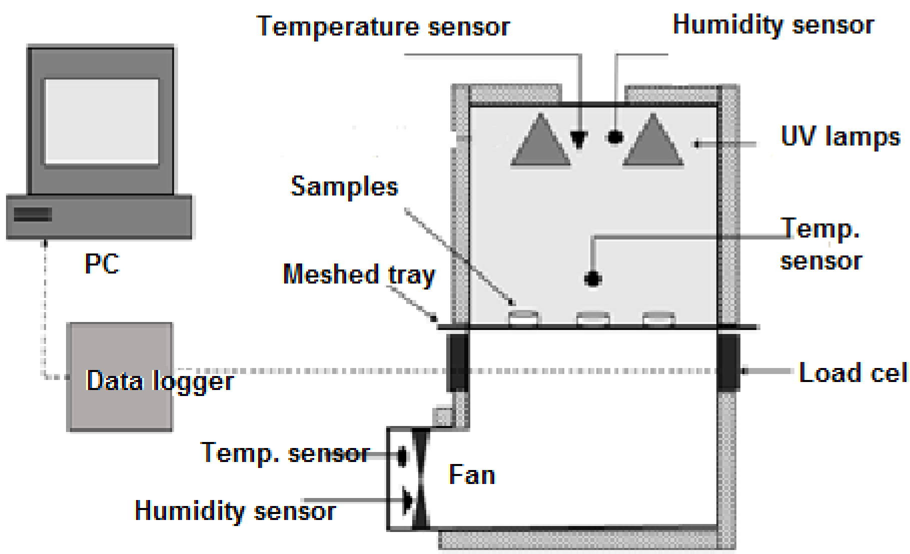

Figure 1. Schematic diagram of infrared dryer for drying apple layers

Investigation of drying kinetics

Before starting each experiment, by placing a sample of apple in the oven at 105 degrees Celsius and drying it until reaching a constant weight, the initial moisture content of the samples was determined using equation (1) and about 0.85 was obtained based on wet matter.

$$M_0 = \frac{w_0 - w_d}{w_0} \tag{1}$$

Where M_0 is the initial moisture based on wet matter (kg water/kg dry matter), w_0 and w_d and the mass of fresh and dry samples (kg), respectively.

For each experiment, about 200 g of sliced apples with a thickness of 5 or 10 mm were placed on a tray and immediately placed inside the dryer. To investigate the effect of different thicknesses and speeds on drying time, factorial experiments were conducted based on a complete random design of three repetitions. In these tests, the thickness at two levels of 5 and 10 mm and the air mass velocity at two levels were considered 0.006 and 0.012 kg/s. The drying process of apples using the three models mentioned in Table 1 expresses the moisture ratio (MR) of apples as a function of time. The moisture ratio is calculated according to the initial moisture (M_0), equilibrium moisture (M_e) and mass moisture at any moment (M), during drying using equation (2):

$$MR = \frac{M - M_e}{M_0 - M_e} \quad (2)$$

Table 1. Models used for drying

Model	model name	Equation	Reference
1	Paige	$MR = \exp(-kt^n)$	Page, (1949).
2	Henderson and Pabis	$MR = a\exp(-kt)$	Henderson and Pabis., (1961).
3	logarithmic	$MR = a\exp(-kt) + b$	Togrul and Pehlivan.,(2002)

To estimate the parameters of each model, MR changes against time were calculated at five-minute intervals and the desired parameters were calculated using the Nonlinear Regression function of Minitab 17 software. The best model was determined by comparing the explanatory coefficient (R^2).

Energy consumption and efficiency

In the dryer used, based on the first law of thermodynamics, the energy consumption rate for drying apple slices is expressed by the following relationship.

$$\dot{E}_t = \dot{E}_{If} + \dot{M}_a(h_{a,i} - h_{a,o}) \quad (3)$$

Where: $\dot{E}_t$ is the total energy consumption rate and $\dot{E}_{If}$ is the infrared power and $\dot{M}_a$ is the mass flow rate of the incoming air, $h_{a,i}$ is the specific enthalpy of the air at the entrance of the dryer chamber and $h_{a,o}$ is the specific enthalpy of the air at the outlet of the drying chamber.

Air mass flow rate is calculated using equation (4):

$$\dot{M}_a = \rho_a V_a A_{dc} \quad (4)$$

Where V_a, A_{dc} are respectively the cross-sectional area of the hot air chamber of the dryer (m^2) and the linear velocity of the air flow entering the dryer chamber, and ρ_a is the density of the dry air, which can be expressed as relation 5 (Naghavi et al., 2010):

$$\rho_a = \frac{101.325}{0.287(T_a + 273.16)} \quad (5)$$

where T_a is the air temperature (°C).

The enthalpy of air at the inlet and outlet of the drying chamber is calculated using relations 6 and 7, respectively (Corzo et al., 2008):

$$h_{a,i} = C_{pa} \,.\, T_{a,i} + W_{a,i}.\, h_w \quad (6)$$

$$h_{a,i} = C_{pa}.\, T_{a,o} + W_{a,o}.\, h_w \quad (7)$$

where C_{pa} is the specific heat of air at constant pressure and $W_{a,i}$ and $W_{a,o}$ respectively are the humidity ratio of wet air at the entrance and exit of the dryer chamber. Also, h_w is the specific enthalpy of water vapor) and $T_{a,i}$ and $T_{a,o}$ are the air temperature at the inlet and outlet of the drying chamber, respectively.

For the specific heat of moist air at constant pressure, we also have (Akpinar, 2004; Corzo et al., 2008):

$$C_{pa} = 1.004 + 1.88\, w \quad (8)$$

Where: 1.004 is the specific heat of air without humidity. The value of humidity ratio of humid air (w) at the inlet and outlet of the dryer chamber is obtained from equations 9 and 11, respectively (Topic, 1995):

$$w_{a,i} = 0.622 \frac{\varphi\, p_{vs}}{p - \varphi\, p_{vs}} \quad (9)$$

Where: p, φ are relative air humidity and air pressure (kpa), respectively, and p_{vs} is saturated vapor pressure, which is defined by equation 10 as a function of air temperature (Zare et al., 2006):

$$p_{vs} = 0.1\exp[27.0214 - \frac{6887}{(Ta + 273.16)} - 5.31\, Ln\left(\frac{Ta + 273.16}{273.16}\right) \quad (10)$$

$$w_{a,o} = w_{a,i} + \frac{\dot{m}_v}{\dot{m}_a} \quad (11)$$

Where: $\dot{m}_v$ is the rate of water evaporation is obtained using equation 12:

$$\dot{m}_v = \frac{w_{t-}w_{t+\Delta t}}{\Delta t} \quad (12)$$

Where: W_t is the mass of the product inside the dryer at time t and $w_{t+\Delta t}$ is the mass of the product at the moment t+Δt, in this research Δt was considered five minutes.

The energy efficiency of the dryer can be calculated from equation (Darvishi et al., 2016; Naghavi et al., 2010):

$$\eta_{en} = \left(\frac{m_w \lambda_w}{E_t}\right) \times 100 \quad (13)$$

where λ_w is the latent heat of water (2257 kJ/kg), E_t is the total energy consumption (kJ) and η_{en} is the energy consumption efficiency of the dryer (%) and m_w is the mass of water vaporized from the product (kg) which was calculated from equation 14:

$$m_w = m_i - m_f \quad (14)$$

Which m_i and m_f are the initial mass and the final mass of the tested samples (kg), respectively.

Calculating exergy and its efficiency

Exergy, in fact, is the amount of power from the total power available in a flow that can be converted into useful work. Exergy analysis is based on the second law of thermodynamics. This law states that energy has quality in addition to quantity. Exergy exists in both the inlet and outlet air streams of a dryer. The values of the exergy rate entering the drying chamber, the exergy rate exiting the drying chamber and the exergy loss rate in the system respectively by relations 15 and 16 and 17 are calculated (Aviara et al., 2014):

$$\dot{Ex}_i = \dot{M}_a\, C_{pa}\left[(T_{a,i} - T_\infty) - T_\infty ln\left(\frac{T_{a,i}}{T_\infty}\right)\right] \quad (15)$$

$$\dot{Ex}_o = \dot{M}_a\, C_{pa}\left[(T_{a,o} - T_\infty) - T_\infty ln\left(\frac{T_{a,o}}{T_\infty}\right)\right] \quad (16)$$

$$\dot{Ex}_L = \dot{Ex}_i - \dot{Ex}_o \quad (17)$$

where: T_∞ is an environment temperature (˚C)

All experiments were performed at an environment temperature of 25±1.2 degrees Celsius and a relative humidity of 22±2.3.

Exergy efficiency (η_{ex}) is also defined as the exergy used to dry the product compared to the input exergy in the dryer system and is calculated using equation 18:

$$\eta_{ex} = \frac{\dot{Ex}_i - \dot{Ex}_L}{\dot{Ex}_i} = 1 - \frac{\dot{Ex}_L}{\dot{Ex}_i} \quad (18)$$

It should be noted that the exergy efficiency of the dryer chamber was not the same as the energy efficiency at different times because the values of (Ex)˙_i and (Ex)˙_o are different at any time. In this research, after the dryer reached a steady state, the exergy of the inlet and outlet air was calculated, and based on that, the exergy consumed and the exergy efficiency of the dryer were determined by using relations (15-18).

RESULTS AND DISCUSSION

As can be seen in table (2), considering the thickness of 5 mm, when the movement speed increases, the drying time increases from 90 minutes to 115 minutes, and for the thickness of 10 mm, from 120 minutes will increase to 130 minutes.

Table 2. Drying time of samples at different mass velocity and thickness

Time (min)	Mass velocity (kg/s)	Mass velocity (kg/s)
90	5	0.006
115	5	0.012
120	10	0.006
130	10	0.012

Table (3) is the analysis of the variance of the data obtained from the examination of variable factors on drying time. According to this table, the effect of thickness, speed and their mutual effect on drying time is significant at 0.01 level.

Table 3. Variance analysis of data obtained from examining variable factors on drying time

Source	Degrees of freedom	Sum of squares	F-Value	P-Value
Thickness	1	968	1936	0.000*
Velocity	1	578	1156	0.000*
Thickness*speed	1	98	196	0.000*
Error	4	2	-	-
Total	7	1646	-	-

*Significant ($p < 0.01$)

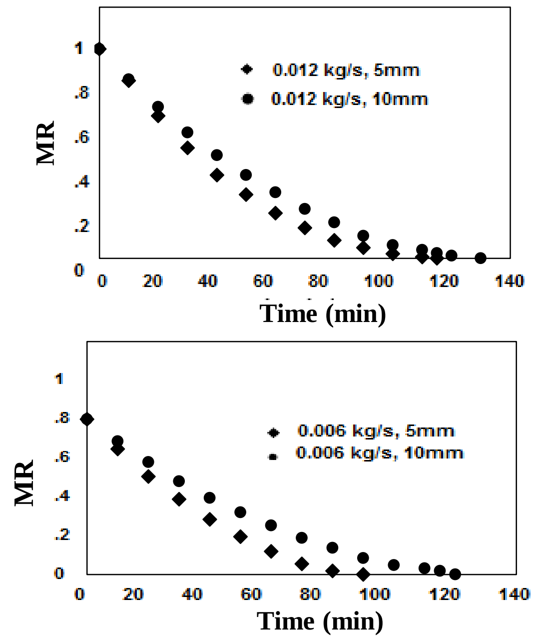

Figure 2. Drying curve of apple thin layer in different thickness and mass rate

The diagram of the drying process of apple slices at two mass velocities of 0.006 and 0.012 kg/s and with two thicknesses of 5 and 10 mm is shown in Figure. 2. The graph shows that by increasing the thickness of the sheets from 5 mm to 10 mm, the drying time has increased by 15 minutes at a mass rate of 0.012 kg and by 30 minutes for 0.006. One of the effective factors in drying with infrared radiation is the thickness and mass velocity of the air. In this method, by increasing the mass velocity of the air, due to the cooling of the product surface by the air flow, the drying speed of the product increases. Cooling the surface of the product reduces the thermal gradient inside the product, and as a result, the drying time of the product increases. Also, with the increase in the thickness of the slices, the moisture path from the depth to the surface of the product increased, as a result, it increased the drying time. Similarly, these results were observed in studies (Akbulut & Durmuş, 2010; Naghavi et al., 2010).

The fitting results of the three models mentioned in table (1) for MR reduction data against time are shown in table (4). The coefficient of explanation obtained for all models was high and no major difference was observed between them. Also, the results showed that all three models were good, but the logarithmic model was the most suitable model for examining the kinetics and predicting the drying process.

Figure 3 shows the amount of energy consumed during the apple drying process at two air mass velocities and two sheet thicknesses. At the beginning, the energy was high in all experiments and decreased with time, which was due to the high rate of moisture loss at the initial moment of drying. As can be seen, drying in thickness of 5 mm with a mass velocity of 0.006 kg/s had the highest energy consumption, while thickness of 5 mm and a speed of 0.012 kg/s had the lowest energy consumption. In general, at the end of the process, there was no significant difference for different energy consumption, and only at the beginning of the experiment, different amounts of energy consumption were obtained. Because in the beginning, the moisture content of the product is high and it takes more energy to evaporate the water. Then the moisture content of the product decreased. The product takes less energy and in return, more energy leaves the dryer with the air flow. At the end of the experiment, by reaching an equilibrium humidity, the consumption values went through a constant trend. When the mass velocity is high, the amount of energy consumed is less. Because in the higher flow, more heat goes out of the system. Therefore, as seen in table (2), the drying time increased with the increase in mass velocity.

Table 4. Coefficients of equations used for drying apple layers

Model	Mass velocity (kg/s)	Thickness (mm)	**k**	**a**	**b**	**n**	**R^2**
$MR = a\exp(-kt) + b$							
	0.006	5	0177912	1/31668	-0.294719	-	0/9990
	0.012	5	0.0187314	1/22660	-0/177146	-	0/9984
	0.006	10	0/0123216	1/3478	-0/334792	-	0/9995
	0.012	10	0/0127675	1/31444	-0.299495	-	0/9991
$MR = \exp(-kt^n)$							
	0.012	5	0/00724773	-	-	1/31642	0/9986
	0.006	5	0/00791872	-	-	1/34055	0/9935
	0.012	10	0/00676683	-	-	1/26932	0/9954
	0.006	10	0/00679161	-	-	1/26864	0/9951
$MR = a\exp(-kt)$							
	0.012	5	0/0268569	1/10273	-	-	0/9863
	0.006	5	0/0306392	1/09443	-	-	0/9768
	0.012	10	0/212681	1/07287	-	-	0/9838
	0.006	10	0/0212896	1/07341	-	-	0/9832

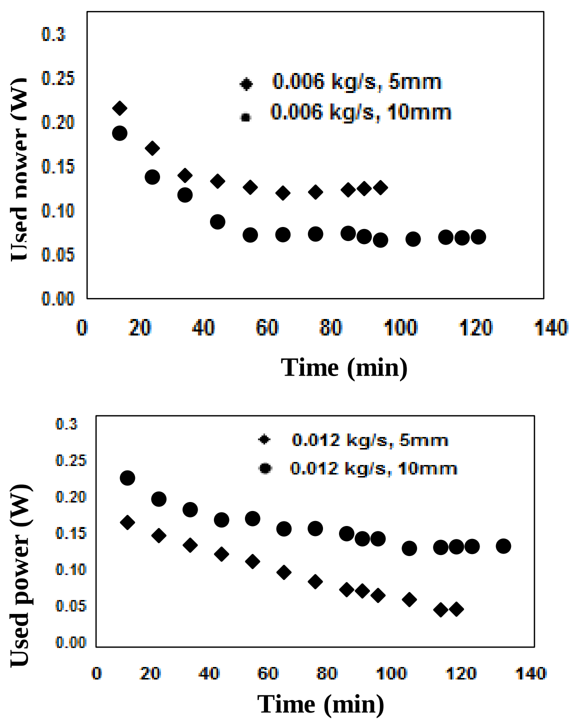

Figure 3. The effect of thickness and different speeds on the energy consumption of the entire drying chamber

Figure 4 shows the changes in the energy efficiency value during the apple drying process at two air mass velocities and two thicknesses of the apple sheet. The efficiency of the consumed energy decreased with the increase of time, because at first, high energy consumption was due to high humidity, and finally, energy efficiency decreased due to low evaporation. Energy efficiency indicates how much energy was used to carry out the drying process under certain conditions compared to the energy in the incoming air. At the beginning of the experiment, energy efficiency values were higher due to high evaporation per unit time. But at the end of the experiment, as the moisture balance approaches, the amount of consumption has gone through a relatively constant trend. As can be seen in Figure. 4, it had the highest energy efficiency at a thickness of 5 mm at a mass velocity of 0.006 kg/s. The thickness of 5 mm and the speed of 0.012 kg/s had the lowest energy efficiency. Because in the beginning, the moisture content of the product is high and it takes more energy to evaporate the water. Next, the moisture content of the product decreases. The product consumes less energy and on the other hand, more energy is released from the dryer with the air flow, which at the end of the test has reached an equilibrium humidity and the consumption values have gone through a constant process. When the mass velocity is high, the amount of energy consumed is less. Because in higher flow, it takes some of the heat out of the system. For this reason, as can be seen in table (2), the drying time increased with the increase in mass velocity.

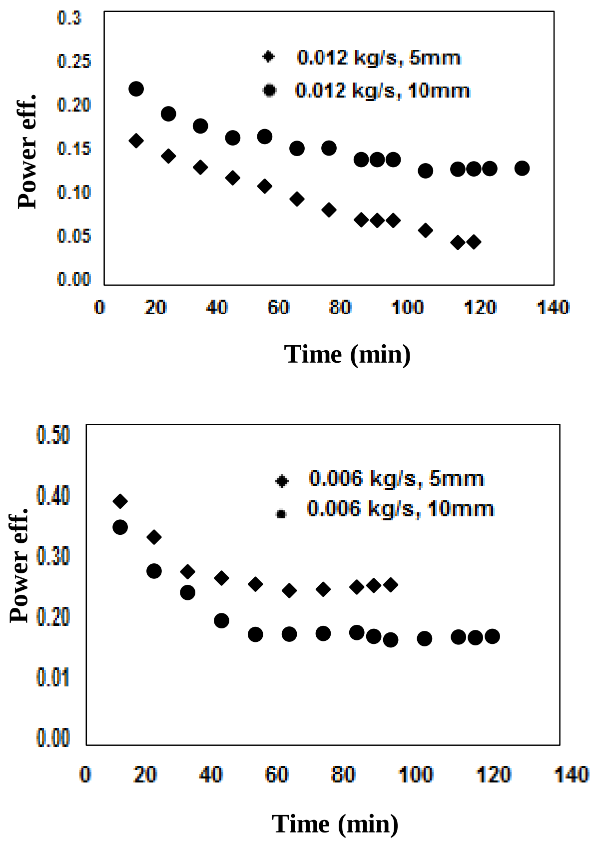

Figure 4. The effect of thickness and different speeds on the energy efficiency of the entire drying chamber

Figure 5 shows the amount of exergy consumed during the apple drying process at two air mass velocities and two apple thicknesses. As it can be seen, the changes of consumed exergy have a decreasing trend, the reason for this is due to the high loss of moisture, which according to relations 13, 8, 11 and 12 has an effect on exergy and consequently on consumed exergy. The consumed exergy of the drying chamber decreased with time. The consumed exergy first increased and then decreased with the passage of drying time. The reason is that the temperature difference between the inlet and outlet of the drying chamber increases at first, which causes more evaporation of the water in the apple layers and more exergy consumption, and then the temperature difference between the inlet and outlet of the drying chamber decreases, as a result evaporation is less and consequently the exergy consumption is less. The highest exergy consumption was related to mass velocity of 0.012 kg/s and thickness of 10 mm, and the lowest exergy consumption was related to mass velocity of 0.006 kg/s and thickness of 10 mm.

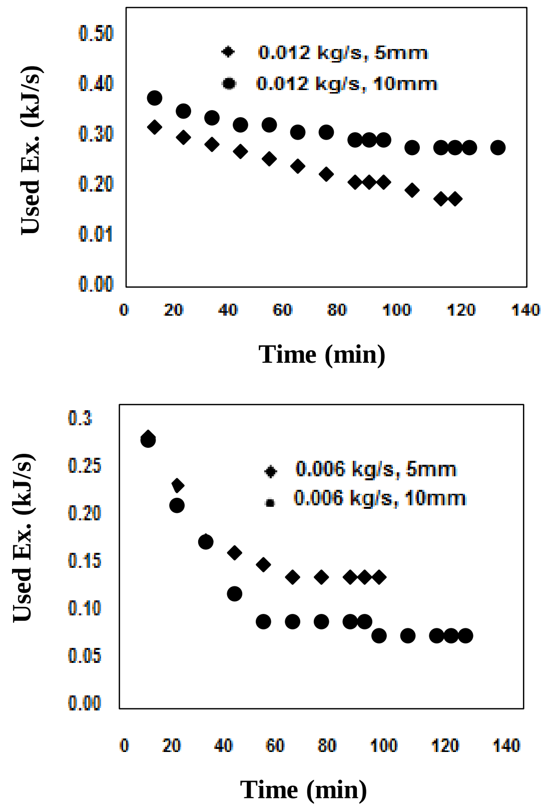

Figure 5. The effect of thickness and different speeds on the exergy consumption of the entire dryer chamber

Figure 6 shows the amount of exergy efficiency during the apple drying process at two air mass velocities and two apple thicknesses. The exergy efficiency decreased during the drying process. The reason for this is the reduction of the moisture content of the product. The exergy efficiency in the dryer chamber also increased at first and then decreased. The reason for this can be explained by the difference between the inlet and outlet temperatures, because the outlet temperature gradually approaches the inlet temperature and decreases. As seen in Figure 6, the highest exergy efficiency is related to the mass velocity of 0.012 kg/s and the thickness of 10 mm. The lowest exergy efficiency was related to mass velocity of 0.006 kg/s and thickness of 10 mm. The reason is that the temperature difference between the inlet and outlet of the drying chamber increases at the beginning, which causes more evaporation of the water in the apple layer and more consumption of exergy efficiency, and then the temperature difference between the inlet and outlet of the dryer The dryer is reduced. As a result, evaporation is less and as a result, the efficiency of exergy consumption is less.

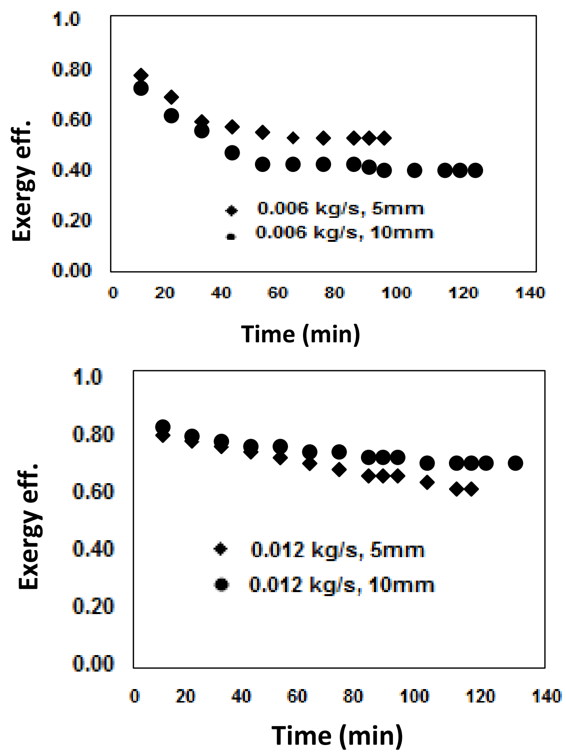

Figure 5. The effect of thickness and different speeds on the exergy efficiency of the entire dryer chamber

CONCLUSION

The results of drying apple slices using infrared radiation showed that air speed, thickness and their interaction have a significant effect on drying time. Fitting the curve to the data and comparing the explanatory coefficients showed that the best model to describe the drying behavior was the logarithmic model. The values of energy consumption and energy efficiency in different thicknesses and mass velocities were very different at the beginning of the experiment, and with the passage of time and the loss and decrease of moisture of the sheets, these values became close to each other. The results of energy and exergy analysis showed that in all treatments, energy consumption, energy efficiency, the amount of exergy consumed and its efficiency decrease. The value of energy efficiency changed between 0.09 and 0.42 and exergy efficiency between 0.01 and 0.81 in different stages. These results showed that a large amount of energy used for drying leaves the system without being used.

REFRENCES

Afzal, T., & Abe, T. (1999). Some fundamental attributes of far infrared radiation drying of potato. *Drying Technology*, *17*(1-2), 138-155.

Aghbashlo, M., Kianmehr, M. H., & Arabhosseini, A. (2008). Energy and exergy analyses of thin-layer drying of potato slices in a semi-industrial continuous band dryer. *Drying Technology*, *26*(12), 1501-1508.

Akbulut, A., & Durmuş, A. (2010). Energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer. *Energy*, *35*(4), 1754-1763.

Akpinar, E. K. (2004). Energy and exergy analyses of drying of red pepper slices in a convective type dryer. *International Communications in Heat and Mass Transfer*, *31*(8), 1165-1176.

Aviara, N. A., Onuoha, L. N., Falola, O. E., & Igbeka, J. C. (2014). Energy and exergy analyses of native cassava starch drying in a tray dryer. *Energy*, *73*, 809-817.

Corzo, O., Bracho, N., Vásquez, A., & Pereira, A. (2008). Energy and exergy analyses of thin layer drying of coroba slices. *Journal of Food Engineering*, *86*(2), 151-161.

Darvishi, H., Zarein, M., & Farhudi, Z. (2016). Energetic and exergetic performance analysis and modeling of drying kinetics of kiwi slices. *Journal of food science and technology*, *53*, 2317-2333.

Das, I., Das, S., & Bal, S. (2004). Specific energy and quality aspects of infrared (IR) dried parboiled rice. *Journal of Food Engineering*, *62*(1), 9-14.

Doymaz, I. (2004). Convective air drying characteristics of thin layer carrots. *Journal of Food Engineering*, *61*(3), 359-364.

Khir, R., Pan, Z., Salim, A., Hartsough, B. R., & Mohamed, S. (2011). Moisture diffusivity of rough rice under infrared radiation drying. *LWT-Food Science and Technology*, *44*(4), 1126-1132.

Naghavi, Z., Moheb, A., & Ziaei-Rad, S. (2010). Numerical simulation of rough rice drying in a deep-bed dryer using non-equilibrium model. *Energy Conversion and Management*, *51*(2), 258-264.

Nazghelichi, T., Kianmehr, M. H., & Aghbashlo, M. (2010). Thermodynamic analysis of fluidized bed drying of carrot cubes. *Energy*, *35*(12), 4679-4684.

Salehi, F., Kashaninejad, M., & Asadi Amirabadi, A. (2015). Investigation of Mass Transfer Kinetics during Combined Hot Air-Infrared Drying of Eggplant Slices. *Innovative Food Technologies (IFT)*, *2*(3), 53-60.

Sharma, G., Verma, R., & Pathare, P. (2005). Thin-layer infrared radiation drying of onion slices. *Journal of Food Engineering*, *67*(3), 361-366.

Topic, R. (1995). Mathematical model for exergy analysis for drying plants. *Drying Technology*, *13*(1-2), 437-445.

Wang, Z., Sun, J., Liao, X., Chen, F., Zhao, G., Wu, J., & Hu, X. (2007). Mathematical modeling on hot air drying of thin layer apple pomace. *Food Research International*, *40*(1), 39-46.

Zare, D., Minaei, S., Zadeh, M. M., & Khoshtaghaza, M. (2006). Computer simulation of rough rice drying in a batch dryer. *Energy Conversion and Management*, *47*(18-19), 3241-3254.