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Effective Moisture Diffusivity, Activation Energy and Energy Consumption in Thin-layer Drying of Jujube (*Zizyphus jujube* Mill)

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ABSTRACT

Jujube (*Zizyphus jujube* Mill), a valuable medicinal plant, is consumed either as fresh fruit or dried product in Iran. Drying jujube guarantees a longer shelf time while preserving its quality to be used in medical and pharmaceutical industries. In this research paper, the influence of several drying conditions on the effective moisture diffusivity, activation energy, energy consumption and required specific energy in the drying of jujube is presented. Temperature levels of 50, 60 and 70 ºC and hot air velocities of 0.5, 1 and 1.5 (m s^{-1}) were used as the treatments. Effective moisture diffusivity of jujube fruit during the drying process was in the range of 1.1532-5.1895×10^{-10} (m^2 s^{-1}) for the first period and 0.4036–2.3064×10^{-10} (m^2 s^{-1}) for the second period. Also, the values of energy of activation in both periods were determined to be between 34.97 and 74.20 (kJ mol^{-1}). The energy consumption and the required specific energy for drying were in the range of 79.1- 92.46 (kW h) and 203.59 – 900.08 (kW h kg^{-1}), respectively. Results show that energy consumption diminished when temperature increased at each air velocity, while it increased with increasing hot air velocity.

Keywords: Activation energy, Effective moisture diffusivity, Energy consumption, Jujube drying.

INTRODUCTION

Jujube a fruit of Rhamnaceae family, is consumed fresh or dried for its high medicinal value. Since 2000 years ago, the usage of fruit, seeds, leaf, skin and root have had extended in the remediation of fever (Omid Beigi, 1997). Post harvest stages of jujube includes a storage period before consumption during which unwanted reactions, mainly regarding the color, occur due to light and temperature effects (Heath and Reieccius, 1986; Park, 1993).

Drying is an old technique for the preservation of agricultural and food products. Due to reduced mass and volume, transportation of dried products is easier than fresh fruits (Koyuncu *et al*., 2007). Solar energy was a usual energy source for the traditional dryers. However, it was riddled with numerous problems including: undesirable variations in food quality, insufficient drying control, long term drying processes, and weak hygienic aspects. Industrial dryers offer numerous advantages such as: on time harvesting, loss reduction in fields, programmable harvesting under unwanted weather conditions, longer shelf life, waste recycling, favorable outputs, decreased costs, and better processing time management. Drying is also a high energy process with a great industrial value (Sahin and Dincer**,** 2002).

Thin layer drying is modified to the drying of grains with hot air (at uniform temperature and moisture conditions). Mathematical modeling of hot air drying is

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commonly based on thin layer drying assumptions (Ozdemir and Devres, 1999).

Drying of fruits depends on their mass and heat transfer specifications. Therefore, moisture diffusion and temperature distribution parameters are essential for the design process, quality control, selection of storage facility, and transportation of fruits. Diffusivity, which is a major parameter in agricultural products, is needed for modeling mass transfer processes such as surface absorption and moisture desorption during the storage period (Rafiee *et al*., 2008). Studies on effective moisture diffusivity, energy of activation, and energy consumption in thin layer drying of vegetables and fruits include: pomegranate (Motevali *et al*., 2010, 2011), figs (Babalis and Belessiotis**,** 2004), corn (Doymaz and Pala**,** 2003), plum (Goyal *et al*., 2007), grapes (Pahavanzadeh *et al*., 2001), Quercus (Tahmasebi *et al*., 2011), Soybean (Rafiee *et al*., 2009), Apple (Mousavi and Javan, 2009), Cuminum cyminum (Zomorodian and Moradi, 2010), palm (Falade and Abbo, 2007), paprika (Ramesh *et al*., 2001) and berberis (Aghbashlo *et al*., 2008). However, there is little information on the drying of jujube fruit, which makes the current research necessary. Therefore, the objective of this study was the determination of effective moisture diffusivity, energy of activation, and energy consumption during the drying process of jujube fruit.

MATERIALS AND METHODS

A laboratory scale hot-air dryer developed at the Biophysical Properties Laboratory of Agricultural Faculty, Tarbiat Modares University (Iran), was used for this study. The dryer consisted mainly of an adjustable centrifugal blower, electrical heating elements (1.5 kW), drying chamber, system controller, an inverter (Parto Sanat, Igbt and Co, Iran) and a sample tray. The dryer had an automatic temperature controller with an accuracy of ±0.1°C (Pooyesh digital instrument**,** TMC 101, Iran). Air velocity was adjusted at values (0.5, 1 and 1.5 m s^{-1}) with an accuracy of ±0.1 m s^{-1} using a Vane probe anemometer, Ljt lutrun **AM**-4204 (Taiwan). Air velocity was fixed by using an inverter that directly acted on the blower motor (1.5 kW). Hot air moved vertically through the horizontal sample tray. Dried samples were manually weighed using an electronic balance having an accuracy of ±0.01 g, (AND GF-600, Japan).

Weighing of the samples was continued until no change was observed between two consecutive weighing. Before starting each experiment, the dryer system was turned on for 30 minutes in order to achieve desirable steady-state conditions. Fresh samples were gathered from Farouj City, north Khorasan (North-East of Iran) and were kept at +5ºC temperature in a refrigerator. The initial moisture content of jujube was determined by oven drying method. The 30 g samples were dried in an oven at the temperature of 105 ± 1ºC. By averaging five repetitions, moisture content of fresh jujube was determined to be 62.5 % dry basis (Doymaz, 2005) at the beginning of the experiments and the final moisture content was fixed at 12 ± 1% dry bases.

Experiments were conducted at three levels of temperature (50, 60 and 70ºC) and three levels of hot air velocity (0.5, 1, and 1.5 m s^{-1}). Relative humidity and the temperature of the environment were 30–37% and 23-28ºC, respectively.

The Fick's second law proposed by Crank for unstable diffusion in spherical shapes can be used for modification of moisture transfer in the drying process (Crank**,** 1975). In this relationship, temperature effects and pressure gradients are ignored and it is assumed that the effective moisture diffusivity is constant and radial. For solution of Fick's law of diffusion, assuming moisture migration only by diffusion, negligible shrinking, constant temperature and diffusion coefficients, and long drying times, Equation (1) is given below (Baroni and Hubinger , 1998; Velic *et al.,* 2003):

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp(-n^2\pi^2\frac{D_{eff}t}{r_o^2}) \quad (1)$$

Where, *MR* is moisture ratio (dimensionless), M_t is moisture content at time, *t* (kg water kg solids^{-1}), M_e is equilibrium moisture content (kg water kg solids^{-1}), M_0 is initial moisture content, n denotes the drying terms (1, 2, 3,…), *t* drying time, D_{eff} effective moisture diffusivity (m^2 s^{-1}) and r_0 is radius of sphere (m), which is assumed to be constant during drying. The mean geometrical diameter of jujube is modified according to Equation (2) (Mohsenin, 1986).

$$D_g = (L \times W \times T)^{\frac{1}{3}} \quad (2)$$

Where, *L, W* and *T* are the major, intermediate and minor diameters of the fruit in mm. The obtained mean geometrical diameter (D_g) was used for the estimation of effective moisture diffusivity. Equation (1) can be rewritten as Equation (3) since the other terms are small enough to be ignored (Babalis and Belessiotis**,** 2004).

$$MR = \frac{6}{\pi^2}\exp(-\pi^2\frac{D_{eff}t}{r_o^2}) \quad (3)$$

Logarithmic simplification of Equation (3) leads to the linear form of Equation (4):

$$\ln(MR) = \ln(\frac{6}{\pi^2}) - (\pi^2\frac{D_{eff}t}{r_o^2}) \quad (4)$$

By plotting the measured data in a logarithmic scale, the effective moisture diffusivity was calculated from the slope of the line as presented in Equation (4).

$$k_1 = \frac{\pi^2 D_{eff}}{r_0^2} \quad (5)$$

Using Arhhenius Equation, as a relationship between temperature and effective moisture diffusivity, energy of activation can be calculated using Equation (6):

$$D_{eff} = D_0\exp(-\frac{E_a}{R_g.T_{abs}}) \quad (6)$$

Where, E_a is energy of activation (kJ mol^{-1}), R_g is the universal gas constant (8.3143 J mol^{-1} K^{-1}), T_{abs} is absolute temperature of the drying medium (K) and D_0 is the line intercept, which is always constant.

The temperature used in Equation 6 is the temperature bounded in the dryer. Therefore, the isothermal condition should be mentioned both in the effective moisture diffusivity and energy of activation. Again, the logarithmic operation can be carried out to obtain the linear form Equation (7):

$$lnD_{eff} = lnD_. - \frac{E_a}{R_g}.\frac{\backslash}{T_{abs}} \quad (7)$$

Plotting lnD_{eff} versus ($1/T_{abs}$) can give a line with slope K_2.

During the test, the dryer energy consumption and the energy required for drying one kilogram of jujube fruit was calculated using Equations (8) and (9). The energy consumption in each period was determined using Equation 8 (Koyuncu *et al*., 2007; Aghbashlo *et al*., 2008; Motevali *et al*., 2011).

$$E_t = A\ \upsilon\ \rho_a\ C_a\ \Delta T\ D_t \quad (8)$$

Where, E_t is the total energy in each drying phase (kW h), *A* is the cross sectional area of the holder (0.0314 m^2), ρ_a is the air density (kg m^{-3}), ΔT is the temperature differences (°C), D_t total time for drying each sample (h) and C_a is the specific heat of air (kJ kg^{-1} °C^{-1}). Energy consumption for drying 1 kg of fresh jujube was obtained using Equation (9):

$$E_{kg} = \frac{E_t}{w_0} \quad (9)$$

Where, E_{kg} is the required specific energy and W_0 is the primary mass of sample.

RESULTS AND DISCUSSION

Figure 1 shows the final drying time versus temperature at constant air velocity. With increase in air temperature and air velocity, drying time was decreased.

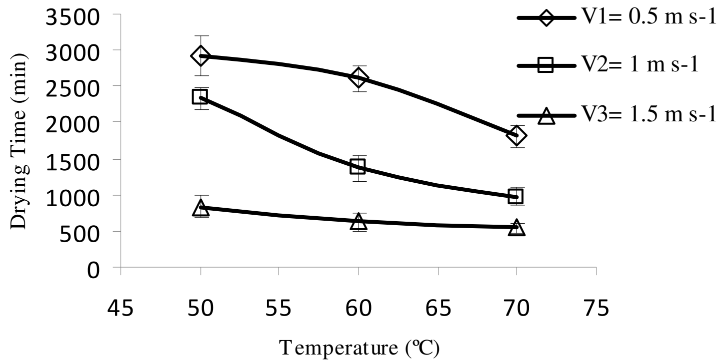

Figure 1. Drying air temperature versus final time at different air velocities for thin-layer drying of jujube fruit.

Typically, drying of agriculture products consists of two phases: a constant rate and a falling rate phase. Furthermore, the major part of the drying process occurs at the falling rate phase. Figure 2 depict plots of *ln(MR)* versus time at the constant air velocity and various temperature levels. The drying rates have more than one falling rate period, which were different from that reported for black tea (Panchariya *et al*., 2002), garlic (Madamba *et al*., 1996) and apricot (Abdelhag and Labuza**,** 1987). Two well-defined falling rate periods are observed, each corresponding to an approximately constant slope from which the effective diffusion coefficients are calculated. This may be due to the capillary property and cell structure of the jujube as indicated by the rate of drying, which was not constant. Effective moisture diffusivity for agricultural and food products falls in the range of 10^{-11} to 10^{-9} m^2 s^{-1}, which includes the range of values obtained in this research (Madamba *et al*., 1996; Wang, *et al* 2007). Effective moisture diffusivities of jujube (Table 1 and 2) fruit during the drying process was in the range of $1.1532\text{-}5.1895\times10^{-10}$ m s^{-1} for the first period

Table 1. Effective moisture diffusivity×(10^{-10} m^2 s^{-1}) and R^2 values at various air temperature and velocity levels.

Air velocity		Temperature					
		50ºC	R^2	60ºC	R^2	70ºC	R^2
0.5 (m s^{-1})	$D_{eff}(1)$	1.15322	0.999	1.72983	0.9908	2.88306	0.9997
	$D_{eff}(2)$	0.403628	0.9938	0.51895	0.9853	0.864917	0.9984
1 (m s^{-1})	$D_{eff}(1)$	1.44153	0.9991	2.30645	0.9996	4.03628	0.9994
	$D_{eff}(2)$	0.51895	0.9795	0.864917	0.9769	1.72983	0.9978
1.5 (m s^{-1})	$D_{eff}(1)$	1.72983	0.9992	2.88306	0.9979	5.1895	0.9981
	$D_{eff}(2)$	0.461289	0.9897	1.15322	0.9858	2.30645	0.9949

Table 2. Linear Equations describing the relationship between effective moisture diffusivity and air velocity in both falling rates at each temperature level.

Temperature (ºC)		Fitted equation	R^2
50	$D_{eff}(1)$	$6\times10^{-11}V+9\times10^{-11}$	R^2= 0.9973
	$D_{eff}(2)$	$6\times10^{-12}V+4\times10^{-11}$	R^2= 0.5915
60	$D_{eff}(1)$	$1\times10^{-10}V+12\times10^{-11}$	R^2= 0.998
	$D_{eff}(2)$	$6\times10^{-11}V+2\times10^{-11}$	R^2= 0.9868
70	$D_{eff}(1)$	$2\times10^{-10}V+2\times10^{-10}$	R^2= 0.999
	$D_{eff}(2)$	$1\times10^{-10}V+8\times10^{-11}$	R^2= 0.999

and 0.4036 - 2.3064×10^{-10} m s^{-1} for the second period (Table 1). It was observed that in the first falling rate, average D_{eff} was greater than in the second falling rate. As can be observed in general from the drying curves and diffusivities, at initial drying stages the removal of moisture from the jujube caused high diffusivity. This result is similar to the findings of Kouchakzadeh (2010) for pistachios drying. With increasing air temperature and velocity, relative moisture content of jujube was decreased due to higher mass and heat transfer within the dryer. Calculations proved that effective moisture diffusivity is highly correlated with hot air temperature and velocity in both periods. The trend demonstrated in Figure (2a-b) shows that, at each velocity, effective moisture diffusivity increases with increasing air temperature in a way that the highest air velocity and temperature levels resulted in the highest effective moisture diffusivity.

The relationship between diffusivity in both falling rates and hot air velocity are given in Table 2. The data are linearly fitted and it is observed that maximum diffusivity occurred at the highest temperature (Figure 3). Effective moisture diffusivity curves versus temperature levels are demonstrated in Figure 4. It is fitted well with the powerequation. The fitted equations and related R^2 values are detailed in Table 3. As shown in Figure 4, effective moisture diffusivity in both falling rates increased with increase in temperature at different air velocities.

Plot of $ln(D_{eff})$ versus $1/T$ is given in Figure 5. Activation energy for jujube was calculated by means of linear regression. The maximum and minimum values of energy of activation in the first period during the drying process were obtained in the ranges of 42.14-50.54 (kJ mol^{-1}) and the maximum and minimum values of energy of activation in the second period were between 34.97 to 74.20 kJ mol^{-1} (Karatas, 1997). The relationships between energy of activation in both falling rates and air velocity are depicted in Figure 6.

The energy consumption and the required specific energy values are demonstrated in Figure 7. As shown in these figure, energy consumption increases with air velocity for each temperature level. temperature, energy consumption increased. Also, energy consumption decreased as temperature increased at constant air velocity. With increasing temperature, the drying time was reduced due to increased thermal gradients inside the material that, consequently,

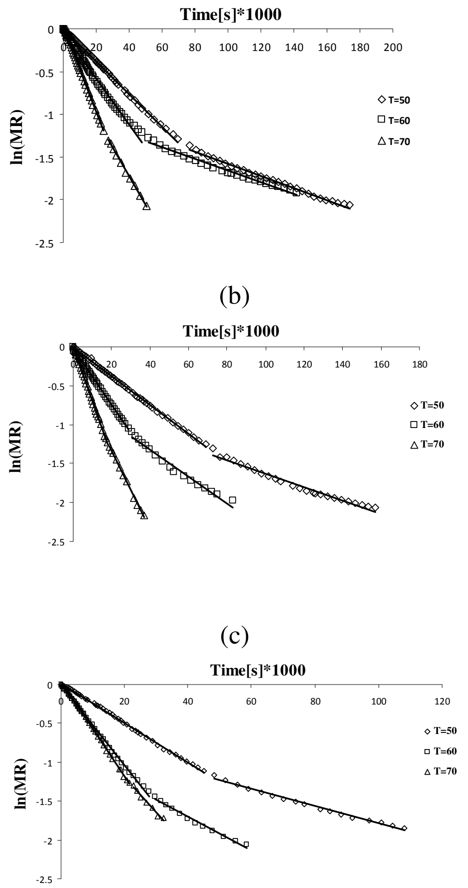

Figure 2. Plot of *ln(MR) vs.* time (s) at air velocity of (a) 0.5 (b)1, and(c)1.5(m s^{-1}).

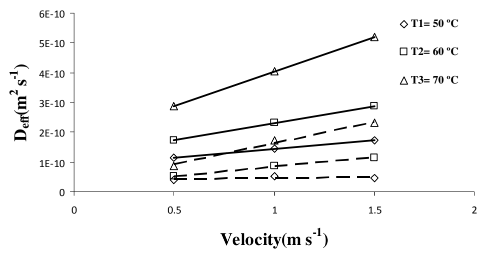

Figure 3. Effect of air temperature and velocity on effective moisture diffusivity. (—): First falling rate,(---): Second falling rate.

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Table 3. Fitted Equations and coefficients of determination for effective moisture diffusivity at the constant air velocity in both falling rates.

Hot air velocity (m s^{-1})		Fitted equation	R^2
0.5	$D_{eff}(1)$	$3\times10^{-15}\,T^{2.7082}$	R^2= 0.9869
	$D_{eff}(2)$	$6\times10^{-15}T^{2.2383}$	R^2= 0.9424
1	$D_{eff}(1)$	$9\times10^{-16}T^{3.0455}$	R^2= 0.9903
	$D_{eff}(2)$	$5\times10^{-17}T^{3.5548}$	R^2= 0.9817
1.5	$D_{eff}(1)$	$5\times10^{-16}T^{3.251}$	R^2= 0.9921
	$D_{eff}(2)$	$3\times10^{-19}T^{4.7906}$	R^2= 0.9990

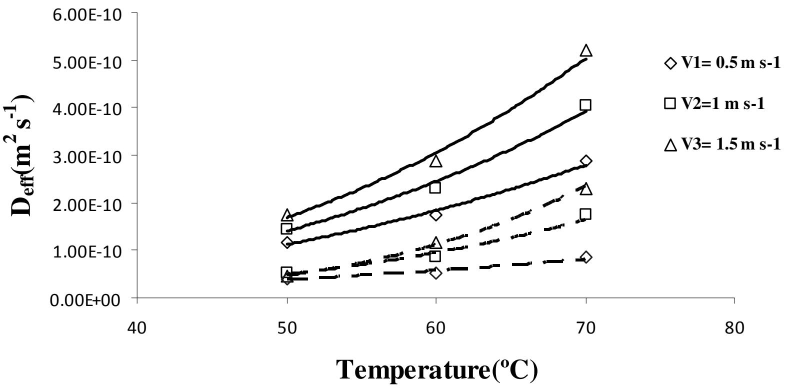

Figure 4. Effective moisture diffusivity plotted versus temperature at different velocity levels.(—):First falling rate, (- - -): Second falling rate.

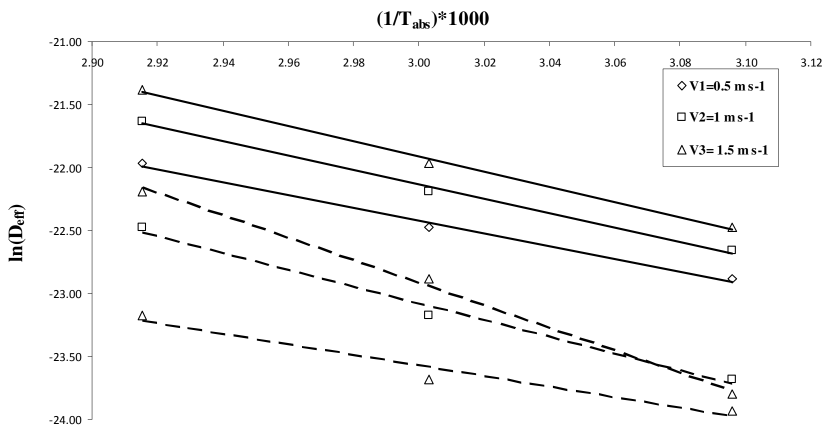

Figure 5. Plot of $ln(D_{eff})$ plotted against $1/T$ at the different air velocitie .(—): First falling rate, (---): Second falling rate.s.

increased the product drying rate. Also, with increase in the hot air velocity, drying time of the product decreased. The cause of this phenomenon is that vapor pressure decreases with increasing air velocity, thereby product moisture faces less resistance to evaporation. The maximum and minimum values in energy consumption were obtained in treatments (T_3:70 C, V_1=0.5 m/s and T_1:50 C, V_3=1.5 m/s).

In Figure 8, using multiple regression analysis, a relationship has been established

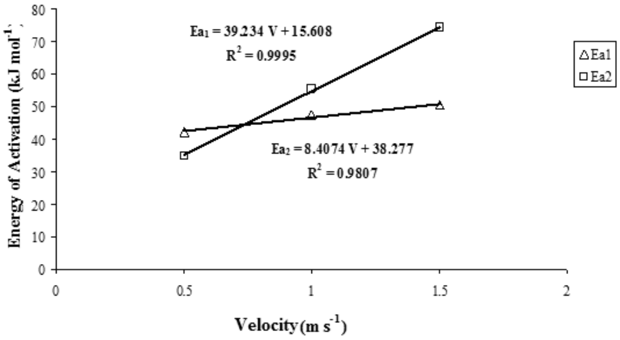

Figure 6. Effect of air velocity on the energy of activation in thin-layer drying of jujube.

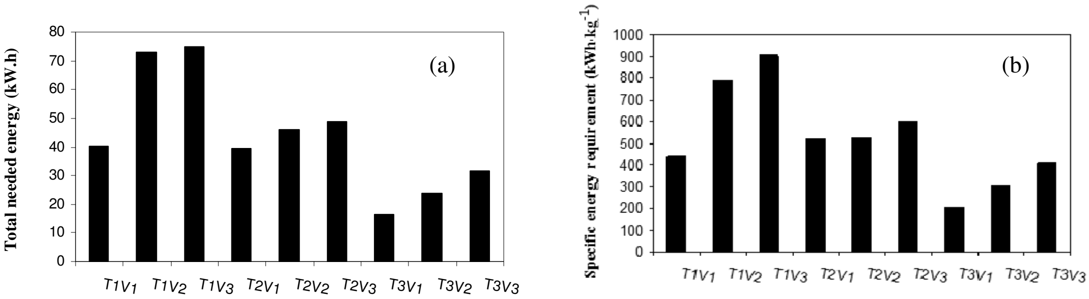

Figure 7. Thin-layer drying of jujube at different levels of air temperature and velocity for (a) energy consumption and (b) required specific energy.

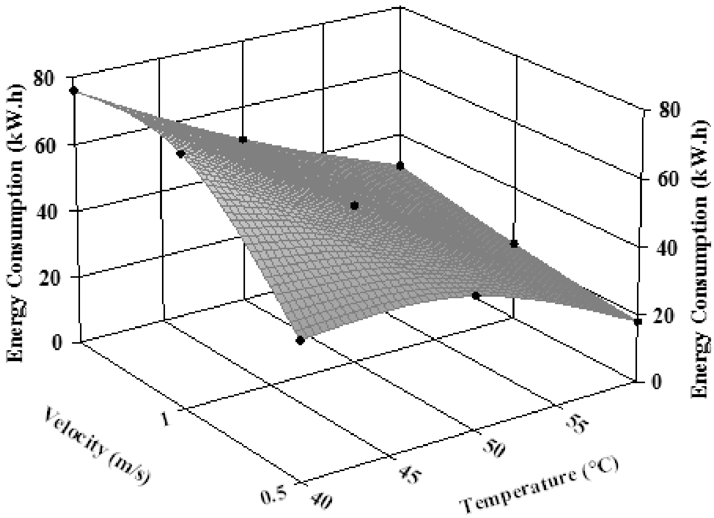

Figure 8. Interaction effect of temperature and air velocity on the energy requirement for hot air of drying jujube fruit.

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between energy consumption, temperature, and air velocity. The corresponding equations and the associated determination coefficient (R^2) are given below.

$$E= -0.444+ 1.05T+126.33V -0.01833T^2- 23.333V^2- 1.2TV \quad (10)$$
$$R^2= 0.95$$

CONCLUSIONS

Moisture diffusivity increased as air temperature and velocity increased.

Energy of activation obtained for the first period was 42.14-50.54 (kJ mol^{-1}) and for the second period 34.97-74.20 (kJ mol^{-1}).

It was observed that energy consumption diminished when temperature increased at each air velocity, while it increased with increasing hot air velocity. It can be concluded that 70 ºC air temperature and velocity of 0.5 m s^{-1} are the optimum parameters for reduction of energy consumption.

Further research would be beneficial in determining the effect of these optimum conditions on medicinal active substances of jujube fruit.

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ضریب نفوذ موثر، میزان انرژی فعال سازی و میزان انرژی مصرفی در خشک کردن لایه نازک عناب(*Zizyphus jujube* Mill)

ع. متولی، ا. عباس زاده، س. مینایی، م. ه. خوش تقاضا و ب. قبادیان

چکیده

عناب به عنوان یک گیاه دارویی با خواص بالا به صورت تازه و خشک مصرف می شود . خشک کردن میوه عناب باعث نگهداری طولانی مدت آن و در نتیجه استفاده طولانی تر آن در صنعت داروسازی و پزشکی می شود .در این مطالعه تاثیرات شرایط مختلف خشک کردن بر روی ضریب نفوذ موثر، انرژی فعال سازی، میزان انرژی مصرفی و انرژی مخصوص مورد نیاز برای خشک کردن گیاه دارویی عناب با استفاده از خشک کن آزمایشگاهی مورد بررسی قرار گرفت . آزمایش‌ها در سه سطح

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دمایی ۵۰ ، ۶۰ و ۷۰ درجه سلسیوس و سه سطح سرعت هوای داغ ۰/۵ و ۱ و ۱/۵ متر بر ثانیه انجام شد .ضریب نفوذ موثر میوه عناب درطی خشک کردن برای دوره اول خشک‌شدن بین ۱/۱۵۳۲ $\times 10^{-10}$ تا ۵/۱۸۹۵ $\times 10^{-10}$ متر مربع بر ثانیه و دوره دوم خشک‌شدن بین ۰/۴۰۳۶ $\times 10^{-10}$ تا ۲/۳۰۶۴ $\times 10^{-10}$ بدست آمد. همچنین انرژی فعال سازی برای دو دوره خشک‌شدن بین ۳۴/۹۷ تا ۷۴/۲۰ کیلوژول بر مول محاسبه شد. میزان انرژی مصرفی برای ۷۹/۱ تا ۹۲/۴۶کیلووات بر ساعت و میزان انرژی مخصوص مورد نیاز برای خشک کردن عناب بین ۲۰۳/۵۹ تا ۹۰۰/۰۸ کیلووات بر کیلوگرم محاسبه شد. نتایج نشان داد که انرژی مصرفی با افزایش دما در هر سرعت هوا کاهش می‌یابد در حالی که با افزایش سرعت جریان هوا در دمای ثابت میزان انرژی مصرفی کاهش می‌یابد.