Determining of moisture diffusivity and activation energy in drying of apricots

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Abstract: In this study, Fick's second law was used as a major equation to calculate the moisture diffusivity for apricot fruit with some simplification. Drying experiments were carried out at the air temperatures of 40, 50, 60, 70, and 80°C and the drying air velocity of 1, 1.5 and 2 m/s. The experimental drying curves showed only a falling drying rate period. The calculated value of the moisture diffusivity varied from 1.7×10^{-10} to 1.15×10^{-9} m^2/s for apricot fruit, and the value of activation energy ranged from 29.35 to 33.78 kJ/mol at different velocities of air.

Keyword: apricots; drying; effective moisture diffusivity; activation energy

Drying is one of the oldest methods of food preservation (Doymaz 2007). It is probably the main and most expensive step in postharvest operations (Cohen & Yang 1995). The objective drying is the removal of water to a level at which microbial spoilage and deterioration reactions are greatly minimised (Akpinar & Bicer 2005). A longer shelf-life, product diversity, and a substantial volume reduction are the reasons for the popularity of dried fruits and vegetables. Thin layer drying Eqs are used to estimate the drying time for several products and also to generalise the drying curves. Drying kinetics is greatly affected by the air velocity, air temperature, material thickness, and others (Erenturk & Erenturk 2007). Physical and thermal properties of agricultural products, such as the heat and mass transfer, moisture diffusion, and activation energy, are required for the ideal dryer design (Aghbashlo *et al.* 2008). Some researchers have studied the moisture diffusion and activation energy in the thin layer drying of various agricultural products, such as seedless grapes (Doymaz & Pala 2002), plums (Goyal *et al.* 2007), grapes (Pahlavanzadeh *et al.* 2001), candle nuts (Tarigan *et al.* 2006), potato slices (Akpinar *et al.* 2003), hazelnuts (Ozedmir & Devres 1999), beriberi fruit (Aghbashlo *et al.* 2008), and onion slices (Pathare & Sharma 2006). Although much information has been given on the effective moisture diffusivity and activation energy for various agricultural products, very little published literature is available on the effective moisture diffusivity and activation energy data for apricots during drying. The knowledge of effective moisture diffusivity and activation energy is necessary for designing and modelling the mass transfer processes such as dehydration or moisture adsorption during storage.

The main objective of this work was to determine the effective moisture diffusivity and activation energy of apricots (cv. *Rajabali*) during thin layer drying process and their dependence on factors such as the air temperature and air velocity.

MATERIAL AND METHODS

Drying experiments

Fresh apricots (cv. *Rajabali*) were obtained from an orchard located in Shahroud, Iran (at a distance of 170 km from Semnan Province) in July 2008. The samples were stored in a refrigerator at +4°C. A schematic diagram of the dryer used in the experiments is shown in Figure 1. The dryer consist of a fan, heaters, air straightener, computer, micro-controller, digital balance, tray, humidity sensor, and thermometer (Yadollahinia 2006). It was

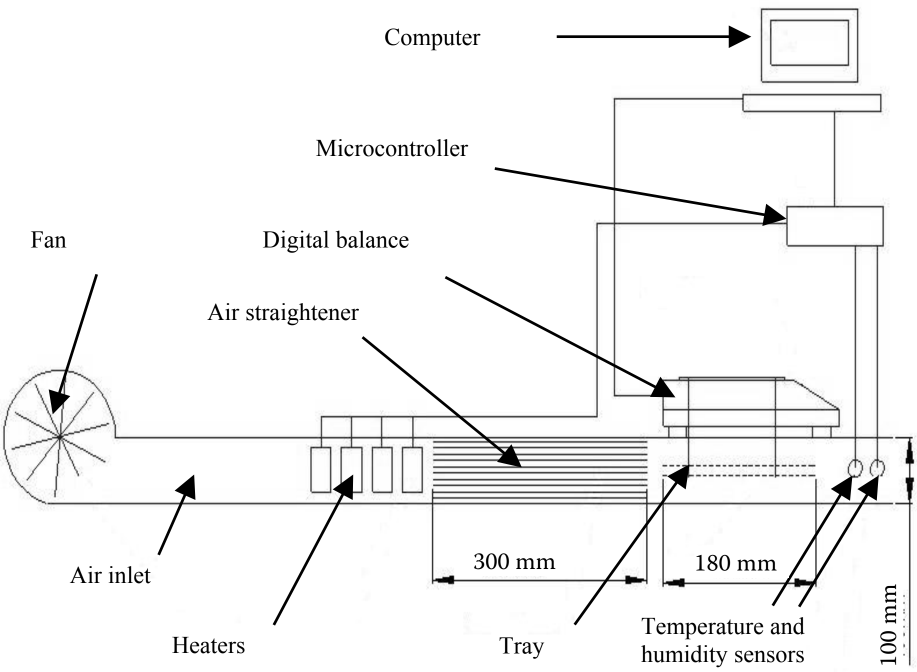

Figure 1. Scheme of thin-layer drying equipment

installed in an environment with the relative air humidity of 20–30% and ambient air temperature varying from 32 to 38°C. During the experiments, the ambient temperature, relative humidity, and inlet and outlet temperatures of air in the dryer chamber were recorded. Prior to the drying process, the samples were washed and their cores were separated, after which the dryer reached the steady state condition; then about 200 g of apricots were placed on the tray of the dryer and left to dry. The drying experiments were carried out at the drying air temperatures of 40, 50, 60, 70, and 80°C and the drying air velocity of 1, 1.5, and 2 m/s. The samples were weighed every 5 s during the process using a digital balance with 0.01 g accuracy. The initial and final moisture contents of the apricots were determined at 78°C during 48 h with the oven method (AOAC 1984). The drying process was terminated when the moisture content decreased to about 15% wet base (w.b) from the initial moisture content value of 84.17% wet base (w.b). In this study, the influence of the mentioned conditions on the effective moisture diffusivity and activation energy in thin-layer drying of apricot fruit (cv. *Rajabali*) was addressed.

Theoretical principle

The drying rate of apricots was calculated using Eq. (1) (Kavak Akpinar 2002):

$$DR = (M_{t+dt} - M_t)/dt \qquad (1)$$

where:

M_{t+dt} – moisture content at the time $t+dt$ (kg water/kg dry mater)

M_t – moisture content at the time t (kg water/kg dry mater)

t – drying time (min)

Crank using Fick's second law proposed Eq. (2) for the effective moisture diffusivity for an infinite slab (Crank 1975):

$$MR = \frac{M}{M_o} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-\frac{(2n-1)^2\pi^2 Dt}{4L^2}\right) \qquad (2)$$

where:

MR – moisture ratio

M – moisture content at any time (kg water/kg dry mater)

M_0 – initial moisture content (kg water/kg dry mater)

n = 1, 2, 3, . . . the number of terms taken into consideration

t – time of drying in seconds

D – effective moisture diffusivity in m^2/s

L – thickness of the slice (m)

Only the first term of Eq. (2) is used for a long drying time (Lopez *et al.* 2000), hence:

$$MR = \frac{8}{\pi^2}\exp\left(\frac{\pi^2 Dt}{4L^2}\right) \qquad (3)$$

The slope (k_0) is calculated by plotting ln(MR) versus time according to Eq. (4):

$$k_o = \frac{\pi^2 D}{4L^2} \qquad (4)$$

The activation energy was calculated using an Arrhenius type equations (Lopez *et al.* 2000; Akpinar *et al.* 2003):

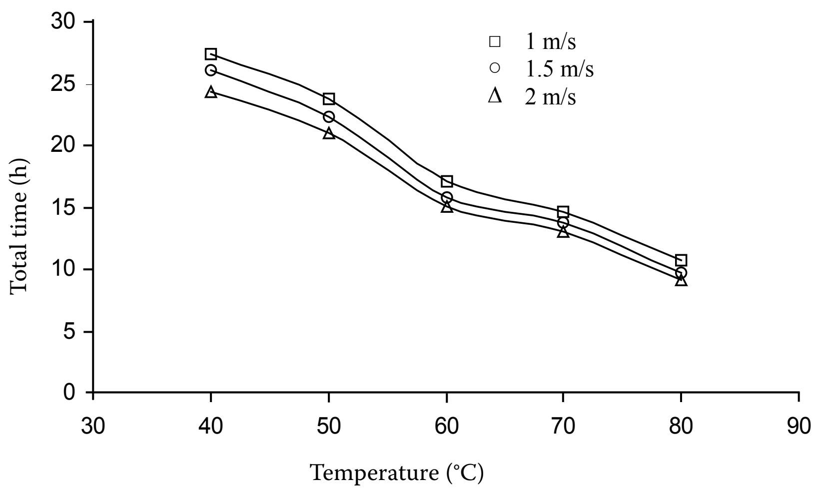

Figure 2. Drying air temperature versus total time at different air velocities

$$D = D_0 \exp\left(-\frac{E_a}{RT_a}\right) \quad (5)$$

where:
E_a – energy of activation (kJ/mol)
R – universal gas constant (8.3143 kJ/mol K)
T_a – absolute air temperature (K)
D_0 – pre-exponential factor of the Arrhenius equation (m^2/s)

From Eq. (5), the plot of ln D versus $1/T_a$ gives a straight slope of K_1.

$$K_1 = E_a / R \quad (6)$$

Linear regression analyses were used to fit the equation to the experimental data to obtain the coefficient of determination (R^2).

RESULTS AND DISCUSSION

Calculation of drying rate

Figure 2 shows total drying time versus temperature at constant air velocity. It is clear that at a low temperature, the difference between total times is significant while at a high temperature, the difference between total times is negligible. In other words, the effect of the air velocity on the drying time at a low temperature is greater than that at a high temperature. The total time at the air velocity of 1 m/s is about 1.3 times longer as compared with experiments performed at 2 m/s at the constant air temperature, whereas it would increase about 2.5–3 times when we compared this total time at 40°C with 80°C at the constant air velocity. In other words, the effect of the air temperature on total drying time is significant, compared with that of the air velocity, in thin-layer drying of apricots.

The variations of the drying rate values with the drying time at different drying air temperatures for air velocities of 1, 1.5 and 2 m/s are presented in Tables 1–3, respectively. All the drying operations are seen to occur in the falling rate period. It is apparent that the drying rate is higher at the beginning of the drying process and decreases continuously with the drying time. These results are in a good agreement with other results reported (Passamai

Table 1. Values of drying rate at different temperatures and different times for air velocity of 1 m/s

Time (min)	Temperature (°C)				
	40	50	60	70	80
0	0.000116	0.000151	0.000201	0.000214	0.000256
150	9.2×10^{-5}	0.000138	0.000168	0.000187	0.000219
300	6.37×10^{-5}	0.000107	0.000119	0.000166	0.000199
450	5.73×10^{-5}	8.89×10^{-5}	9.08×10^{-5}	0.000111	0.000142
600	4.37×10^{-5}	6.47×10^{-5}	7.45×10^{-5}	8.48×10^{-5}	0.000101
750	3.47×10^{-5}	4.63×10^{-5}	5.61×10^{-5}	8.02×10^{-5}	8.89×10^{-5}
900	3.07×10^{-5}	3.32×10^{-5}	5.64×10^{-5}	6.61×10^{-5}	8.63×10^{-5}

Table 2. Values of drying rate at different temperatures and different times for air velocity of 1.5 m/s

Time (min)	Temperature (°C)				
	40	50	60	70	80
0	0.000199	0.000209	0.000281307	0.000326	0.00345
150	0.000111	0.000179	0.000197794	0.000217	0.000250399
300	8.89×10^{-5}	0.0001	0.000156406	0.000195	0.000201861
450	7.61×10^{-5}	8.48×10^{-5}	8.844×10^{-5}	0.000123	0.000133861
600	6.14×10^{-5}	6.93×10^{-5}	7.195×10^{-5}	7.83×10^{-5}	7.991×10^{-5}
750	3.58×10^{-5}	4.43×10^{-5}	5.129×10^{-5}	6.58×10^{-5}	7.389×10^{-5}
900	4.38×10^{-6}	7.88×10^{-6}	2.039×10^{-5}	3.68×10^{-5}	3.986×10^{-5}

Table 3. Values of drying rate at different temperatures and different times for air velocity of 2 m/s

Time (min)	Temperature (C°)				
	40	50	60	70	80
0	0.000202	0.000217	0.000231	0.000329	0.000352174
150	0.000133	0.000141	0.000175	0.00024	0.000273
300	0.00011	0.000133	0.000157	0.000215	0.00023
450	5.9×10^{-5}	7.2×10^{-5}	8.66×10^{-5}	0.000108	0.000124
600	4.71×10^{-5}	6.61×10^{-5}	7×10^{-5}	9.55×10^{-5}	9.69×10^{-5}
750	4.62×10^{-5}	4.76×10^{-5}	4.92×10^{-5}	6.44×10^{-5}	7.91×10^{-5}
900	2.81×10^{-5}	2.95×10^{-5}	3.28×10^{-5}	4.96×10^{-5}	6.99×10^{-5}

& Saravia 1997; Kaymak-Ertekin 2002). The drying rate increased with an increase in the temperature of the drying air, the highest values of the drying rate having been obtained at the drying air temperature of 80°C in all experiments. An increase in the drying rates with an increase in temperature was reported in earlier studies by Pathare and Sharma (2006) for onion slices, Mohapatra and Rao (2005) for parboiled wheat, Doymaz (2005) for green bean.

Calculation of effective moisture diffusivity

The effective moisture diffusivity was calculated using Eq. (4). The minimum value of the moisture diffusivity was 1.7×10^{-10} m^2/s at the air velocity of

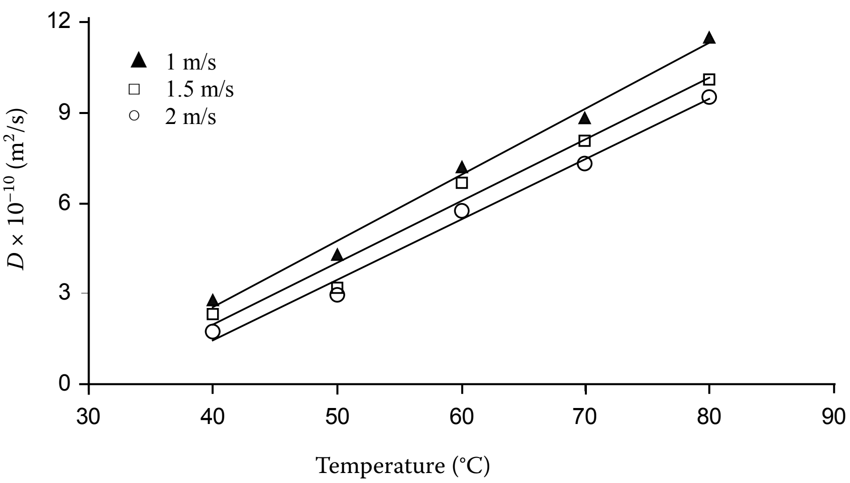

Figure 3. *D* versus temperature at different levels of air velocity for thin-layer drying of apricot

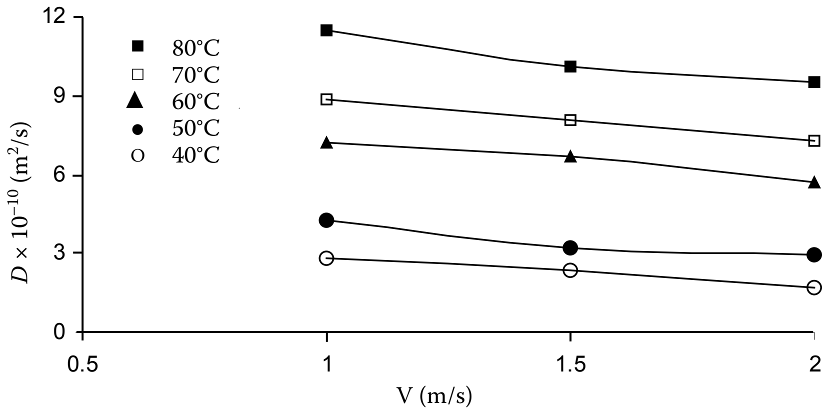

Figure 4. D versus air velocity at different levels of air temperature for thin-layer drying of apricot

Table 4. Fitted equations for D value at constant air velocity

V (m/s)	Equation	R^2
1	$D = 0.0011T^2 + 0.0821T - 2.25$	0.99
1.5	$D = 0.0006T^2 + 0.126T - 3.68$	0.96
2	$D = 0.0006T^2 + 0.126T - 4.43$	0.99

2 m/s and air temperature of 40°C while the maximum value of the moisture diffusivity was 1.15×10^{-9} m²/s at the air velocity of 1 m/s and air temperature of 80°C. Generally, the value of D changes in the range of 10^{-11}–10^{-9} m²/s for food materials (Babalis & Belessiotis 2004; Aghbashlo *et al.* 2008). As seen in Figure 3, the values of D are plotted versus temperature at different levels of air velocity. Second degree polynomial equation was fitted for the calculated values of D. The fitted Eqs and related R^2 are given in Table 4. In Figure 4, the values of D at different levels of air temperature are plotted versus air velocity. As seen, the minimum value of D was found at the minimum air temperature while at constant temperature values an increase in the air velocity decreased D value because at a low air velocity (1 m/s), the air has a better contact with the sample surface which results in a greater absorption of moisture, consequently the moisture gradient of the sample with ambient increases and that leads to an increase in the moisture diffusivity. But at a high air not clear velocity level (2 m/s), the air passing through the sample is turbulent to some extent, therefore the moisture gradient tends to decrease and the moisture diffusivity accordingly reduces.

Based on the independent variables (drying air temperature and drying air velocity) and using a multivariate regression technique, the effective moisture diffusivity was estimated as follows.

$$D = (-3.9 - 1.48V + 0.204T) \times 10^{-10} \qquad R^2 = 0.97$$

Similar findings about the effects of air temperature and velocity on the effective moisture diffusivity were reported by some authors Sacilik and Elicin (2006) for organic apple slices, Corzo *et al.* (2008) for coroba slices, and Aghbashlo *et al.* (2008) for beriberi fruit.

Calculation of activation energy

Table 5 contains the value of ln D versus $1/T_a$ for the air velocities of 1, 1.5, and 2 m/s. The activation energy was calculated using Eq. (6). The values of the activation energy lie from 12.7 to 110 kJ/mol for most food materials (Zogzas 1996). Bablis *et al.* (2004) reported this value varying from 30.8 to 48.47 kJ/mol for figs. Aghbashlo et al. (2008) reported that this

Table 5. Value of ln D versus $1/T_a$ for air velocity of 1, 1.5, and 2 m/s

ln(D)			$1/(T_a)$
V = 2 m/s	V = 1.5 m/s	V = 1 m/s	
–22.4735	–22.0419	–21.9441	313
–21.9402	–21.6649	–21.5740	323
–21.2812	–21.1264	–21.0644	333
–21.0394	–20.9360	–20.8466	343
–20.7705	–20.7079	–20.5835	353

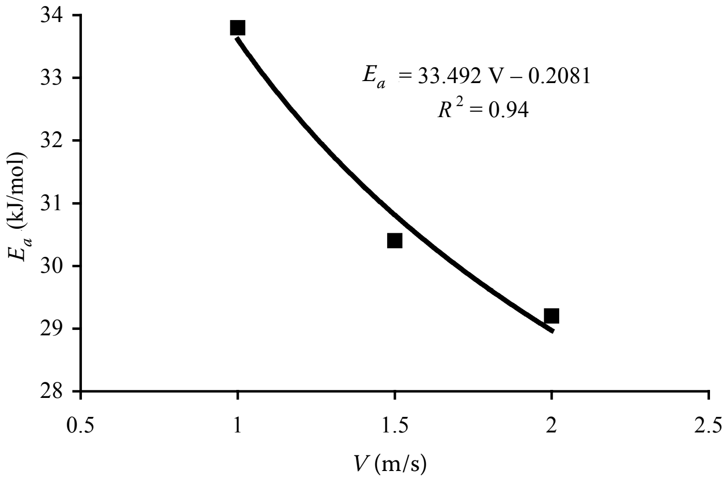

Figure 5. The influence of air velocity on activation energy value for thin–layer drying of apricot

Table 6. Activation energy for different levels of air velocity

Air velocity (m/s)	E_a (kJ/mol)	R^2
1	33.78	0.96
1.5	30.14	0.94
2	29.35	0.98

value varied within 110.837–130.61 kJ/mol for different air velocities with beriberi fruit. Garau *et al.* (2006) reported this value as 36.4 kJ/mol for orange skin. In the present study, the value of E_a varied from 29.35 to 33.78 kJ/mol at different values of air velocities for apricot fruit (Table 6). The variation of the activation energy values versus air velocities is plotted in Figure 5. The relationship between the activation energy and drying air velocity was found by regression analysis. The results indicated that the power equation can predict E_a based on the drying air velocity with R^2 of 0.94.

CONCLUSIONS

In the present study, the drying of apricots was carried out only in the falling rate stage. This implies that the moisture removal from the product was governed by diffusion phenomenon. The highest effective diffusion was found to be 1.15×10^{-9} m^2/s at the air temperature and air velocity of 80°C and 1 m/s, respectively. The lowest effective diffusion was 1.7×10^{-10} m^2/s at the air temperature and air velocity of 40°C and 2 m/s, respectively. It was deduced that at a low air velocity (1 m/s) the air has a better contact with the sample surface which results in a greater absorption of moisture, consequently the moisture gradient of the sample with ambient increases and that leads to an increase in the moisture diffusivity. But at a high air velocity level (2 m/s), the air passing through sample is turbulent to some extent, therefore the moisture gradient tends to decrease and the moisture diffusivity accordingly reduces. The activation energy for the apricot fruit in the drying experiments varied from 29.35 to 33.78 kJ/mol.

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Abstrakt

Mirzaee E., Rafiee S., Keyhani A., Emam-Djomeh Z. (2009): **Stanovení difuzivity vlhkosti a aktivační energie při sušení meruněk**. Res. Agr. Eng., **55**: 114–120.

Ve studii byl použit druhý Fickův zákon s určitým zjednodušením jako nejvýznamnější rovnice pro výpočet difuzivity vlhkosti v meruňkách. Sušící experimenty proběhly při teplotách 40, 50, 60, 70 a 80°C a při rychlosti sušícího vzduchu 1, 1.5 a 2 m/s. Pokusné sušící křivky ukázaly pouze časové období klesající rychlosti sušení. Při rozdílných rychlostech vzduchu se vypočtené hodnoty difuzivity vlhkosti v meruňkách pohybovaly v rozmezí 1,7 × 10^{-10} až 1,5 × 10^{-10} m^2/s a hodnoty aktivační energie v rozmezí 29,35 až 33,78 KJ/mol.

Klíčová slova: meruňky; sušení; efektivní difuzivita vlhkosti; aktivační energie

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