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Drying of apple slices (var. Golab) and effect on moisture diffusivity and activation energy

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Abstract

Drying is one of the primary methods of food preservation. Determining coefficients used in drying models is essential to predict the drying behaviour. The present study was conducted to compute effective moisture diffusivity and activation energy of samples of apple slices. The thin-layer drying experiments were carried out under five air temperatures of 40, 50, 60, 70 and 80ºC, three air velocities of 0.5, 1.0 and 2.0 m/s and three apple slice thicknesses of 2, 4 and 6 mm and constant air humidity of 21%. Results indicated that drying took place in the falling rate period. Moisture transfer from apple slices was described by applying the Fick's diffusion model. The effective diffusivity values for all conditions changed from 1.50×10^{-8} to 1.71×10^{-7}m²/s. An Arrhenius relation with an activation energy value of 22664.1 to 30919.0 J/mol and the diffusivity constant value of 1.16×10^{-4} to 6.34×10^{-3} m²/s were obtained which shows the effect of drying air temperature, air velocity and slice thickness on the diffusivity.

Keywords: Apple, activation energy, moisture diffusivity, thin layer, Page model

Introduction

Drying, as a complex process involving heat and mass transfer phenomena and frequent in most food processing industries (Cohen and Yang, 1995), is probably the main and the most expensive step in postharvest tasks. It improves the product shelf life without the addition of any chemical preservative and reduces both the size of package and transport costs.

Mathematical modeling and simulation of drying curves under different conditions is important to obtain a better control of this unit operation and an overall improvement of the quality of the final product. Models are often used to study the variables involved in the process, predict drying kinetics of the product and to optimize the operating parameters and conditions (Karathanos and Belessiotis, 1999). Drying process of food materials mostly occurs in the falling rate period (Wang and Brennan, 1992). To predict the moisture transfer during the falling rate drying period, several mathematical models have been proposed using Fickian's diffusion, as shown in Eq. 1, as a basis to describe the moisture transport process (Doymaz, 2006; Gou et al., 2003; Maskan et al., 2002; Sablani et al., 2000; Saravacos and Charm, 1962; Sacilik, 2007 ; Srikiatden and Roberts, 2006). Moisture transfer during drying is controlled by internal diffusion (Saravacos and Charm, 1962):

$$\frac{\partial M}{\partial t} = \nabla\left[D_{eff}\left(\nabla M\right)\right] \quad (1)$$

where: D is effective moisture diffusivity in m²/s, t is time in second and M is moisture content of the product in kg water/kg dry solid. The effective moisture diffusivity is representing the conductive term of all moisture transfer mechanisms. This parameter is usually determined from experimental drying curves (Doymaz, 2006; Gou et al., 2003, Maskan et al., 2002, Sablani et al., 2000, Saravacos and Charm, 1962; Sacilik, 2007; Srikiatden and Roberts, 2006). The diffusion coefficient of a food product is a material property and its value depends upon the conditions within the material. Effective moisture diffusevity describes all possible mechanisms of moisture movement within the product, such as liquid diffusion, vapor diffusion, surface diffusion, capillary flow and hydrodynamic flow (Kim and Blowmilk, 1995). Moisture transport which involves diffusion of moisture in solid foods is a complex process. Temperature dependence of the effective diffusivity has been shown to follow an Arrhenius relationship (Sacilik, 2007; Srikiatden and Roberts, 2006; Kim and Blowmilk, 1995; Jason, 1958; Pathare and Sharma, 2006; Lopez et al., 2000 and Simal et al., 1996):

$$D = D_0 \exp\left(-\frac{E_a}{RT_a}\right) \quad (2)$$

where: D_0 is the pre-exponential factor of the Arrhenius equation in m^2/s, E_a is the activation energy in kJ/mol, R is the universal gas constant in kJ/mol K and T_a is the absolute air temperature in K. The activation energy can be determined from the slope of the Arrhenius plot, ln(D) vs. 1/T. The temperature used in the Arrhenius analysis is the ambient

Table 1. Specifications of measurement instruments including their rated accuracy

Instrument	Model	Accuracy	Make
Digital balance	GF3000	± 0.02 g	A&D, Japan
T-sensor	LM35	$\pm 1^{o}C$	NSC, USA
RH-sensor	Capacitive	$\pm 3\%$	PHILIPS, UK
V-sensor	405-V1	$\pm 3\%$	TESTO, UK

Table 2. Values of constants and coefficients of linear and nonlinear model for different temperatures

Temperature (ºC)	a	b	c	R^2
80[1]	-0.0087	0.0084	8.3E-05	0.896
70[1]	-0.0019	0.0023	6.3E-05	0.634
60[1]	-0.0031	0.0031	2.1E-05	0.957
50[2]	-	0.0003	-2.E-06	0.323
40[2]	-	0.0002	2.7E-07	0.315

[1] $DR = aM^2 + bM + c$

[2] $DR = bM + c$

temperature of drying, thus assuming that the temperature of the material being dried is also that of the surrounding drying environment. Therefore, the isothermal assumption has been applied in both determining the effective diffusivity and the activation energy.

Potatoes and carrots have shown to develop negligible porosity during drying (Zogzas et al., 1996) and thus will be representative hygroscopic, non-porous materials in this study. The overall objectives of this research were to compare traditionally measured effective diffusivity using convective hot air to effective diffusivity measured under isothermal conditions using potato and carrot (core and cortex).
Very little published literature is available on effective diffuseivity data for apple slices during drying. A knowledge of effective moisture diffusivity is necessary for designing and modeling mass transfer processes such as dehydration, adsorption and desorption of moisture during storage.

The aim of this work was to determine the effective moisture diffusivity and activation energy of apple (Golab variety) slices during drying process and its dependence on factors such as air temperature, air velocity and thickness of apple that essentially influence the drying rate. Also, this paper was illustrated relationship between drying rate, moisture content and air temperature in the constant air humidity and relationship between effective diffusivity and temperature.

Materials and methods

Apple slices were considered as an infinite slab because the thickness of the slice (2, 4 and 6 mm) was much less than its diameter (about 55 mm). The moisture diffusivity for an infinite slab was therefore calculated by Eq. 3, considering assumptions mentioned hereunder (Pathare and Sharma, 2006; Lopez et al., 2000; Simal et al., 1996; Zogzas et al., 1996 and Sharma et al., 2005):
(1) Moisture is initially distributed uniformly throughout the mass of a sample.
(2) Mass transfer is symmetric with respect to the center.
(3) Moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air.

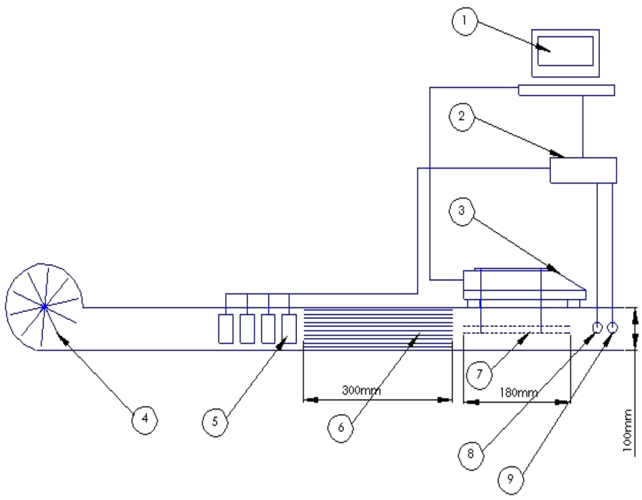


Fig 1. Schematic diagram of the drying system for measurement of the thin-layer parameters of apple slices. 1. PC; 2. micro - controller; 3. digital balance; 4. fan; 5. heating elements; 6. duct and tunnel; 7. trays; 8. temperature sensor; 9. relative humidity sensor.

(4) Resistance to the mass transfer at the surface is negligible compared to internal resistance of the sample.
(5) Mass transfer is by diffusion only.
(6) Diffusion coefficient is constant and shrinkage is negligible.

$$MR = \frac{M}{M_0} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-\frac{(2n-1)^2\pi^2 Dt}{4L^2}\right) \qquad (3)$$

where: MR is the moisture ratio, L is the thickness of slice (m) and n is a positive integer. Only the first term of Eq. 3 is used for long drying times (Lopez et al., 2000):

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

Table 3. Effective diffusivity of apple slice in different drying conditions

Slice thickness (mm)	drying air Velocity (m/s)	Effective diffusivity (m^2/s)				
		40ºC	50ºC	60ºC	70ºC	80ºC
2	0.5	1.50×10^{-8}	2.68×10^{-8}	3.39×10^{-8}	4.42×10^{-8}	4.89×10^{-8}
2	1.0	1.71×10^{-8}	2.26×10^{-8}	3.03×10^{-8}	4.50×10^{-8}	4.76×10^{-8}
2	2.0	1.93×10^{-8}	2.89×10^{-8}	3.66×10^{-8}	5.15×10^{-8}	5.94×10^{-8}
4	0.5	3.15×10^{-8}	4.82×10^{-8}	6.27×10^{-8}	7.66×10^{-8}	9.79×10^{-8}
4	1.0	3.40×10^{-8}	4.39×10^{-8}	5.99×10^{-8}	7.87×10^{-8}	1.11×10^{-7}
4	2.0	3.25×10^{-8}	5.44×10^{-8}	7.08×10^{-8}	9.45×10^{-8}	1.28×10^{-7}
6	0.5	4.58×10^{-8}	6.66×10^{-8}	9.05×10^{-8}	1.26×10^{-7}	1.62×10^{-7}
6	1.0	3.81×10^{-8}	6.30×10^{-8}	8.96×10^{-8}	1.15×10^{-7}	1.57×10^{-7}
6	2.0	4.73×10^{-8}	7.39×10^{-8}	7.23×10^{-8}	1.27×10^{-7}	1.71×10^{-7}

Table 4. Diffusivity constant and activation energy for apple slice (Golab) for different slice thickness and air velocities

Thickness(mm)	Velocity(m/s)	Diffusion constant, D_0 (m^2/s)	Activation energy, E_a (J/mol)
2	0.5	1.16×10^{-4}	22664.1
	1.0	1.58×10^{-4}	23633.4
	2.0	2.55×10^{-4}	24457.3
4	0.5	3.32×10^{-4}	23848.1
	1.0	1.82×10^{-3}	27770.4
	2.0	1.74×10^{-3}	28551.9
6	0.5	2.80×10^{-3}	28610.7
	1.0	4.26×10^{-3}	29946.1
	2.0	6.34×10^{-3}	30919.0

The slope (k_0) is calculated by plotting ln(MR) versus time according to Eq. 5:

$$k_0 = \frac{\pi^2 D}{4L^2} \quad (5)$$

Preparing samples

In this research, a thin layer laboratory dryer is used which has recently been designed and built in the Department of Agricultural Machinery at University of Tehran. Schematic diagram of the dryer system is shown in Figure 1, A portable, 0-15 m/s range digital anemometer (TESTO, 405-V1) was used to occasionally measure air flow velocity of air passing through the system. The airflow was adjusted by means of a variable speed blower. The heating system was consisted of four heating elements placed inside the duct. A simple control algorithm was used to control and adjust the drying tunnel temperature. The opening side on the right was used to load or unload the tunnel and to measure drying air velocity. The trays were supported by lightweight steel rods placed under the digital balance (Yadollahinia, 2006).

Measured variables were air temperature, air velocity, relative humidity (RH), and sample mass loss during drying. Specifications regarding the measurement instruments include-ing their rated accuracy are summarized in Table 1. After turning on the computer, fan, scale, elements and data acquisi-

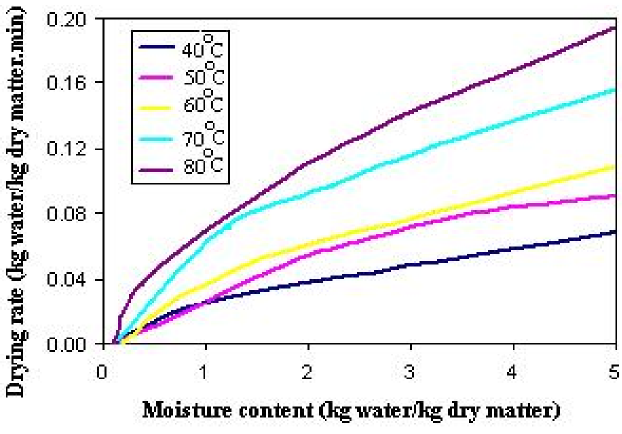
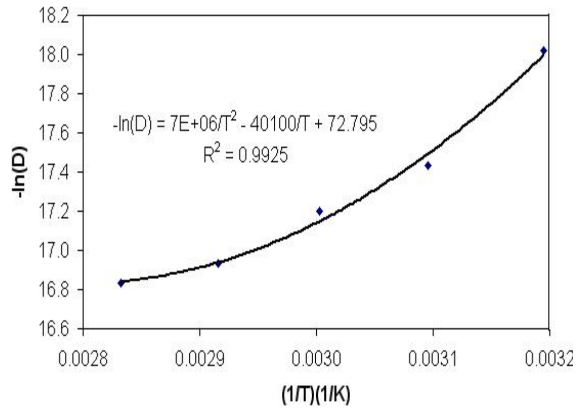
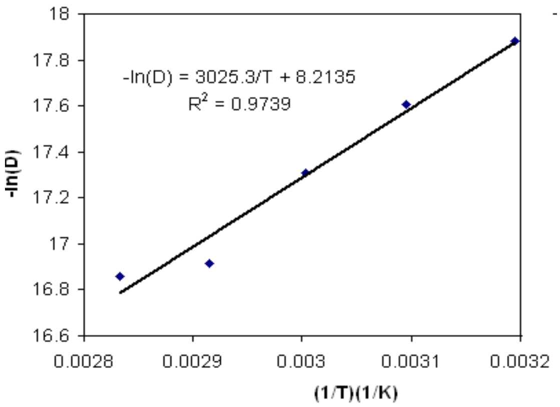


Fig 2. Influence of temperature on drying rate of apple slices at five temperatures of 40°C, 50 °C, 60 °C, 70 °C and 80 °C, for 2 mm thickness and velocity of 0.5 m/s.

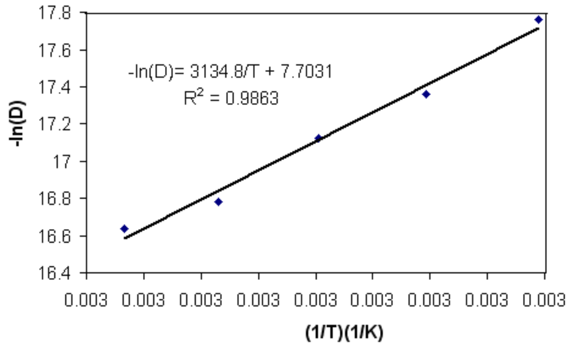
tion system, the essential velocity for the fan was set. A manual TESTO 405-V1 model sensor was used to measure the velocity. The control software was implemented and the required temperature for the experiment was adjusted. Experiments were carried out 30 minutes after the system was turned on to reach



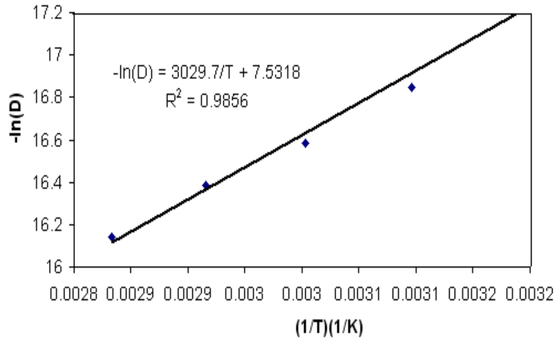
a- Air velocity at 0.5m/s and thickness slice at 2 mm



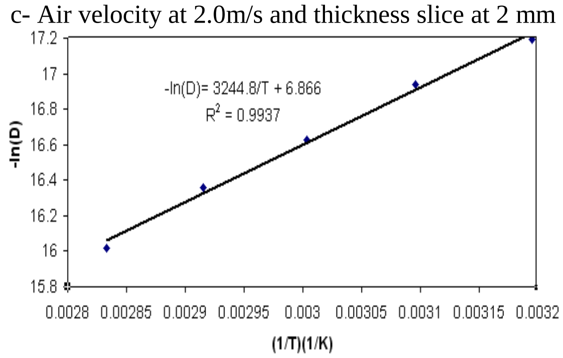
b- Air velocity at 1.0m/s and thickness slice at 2 mm



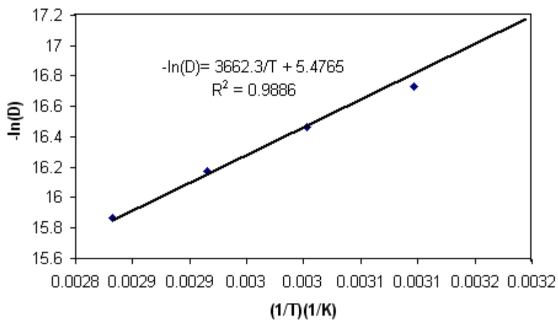
c- Air velocity at 2.0m/s and thickness slice at 2 mm



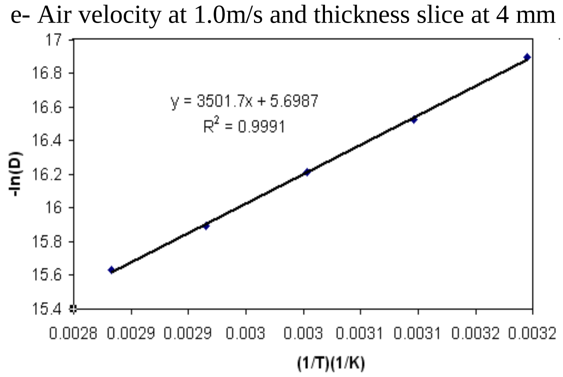
d- Air velocity at 0.5m/s and thickness slice at 4 mm



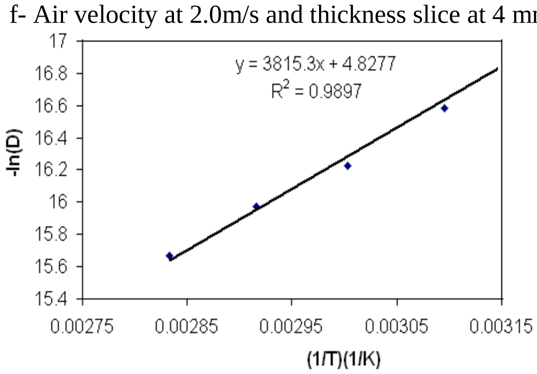
e- Air velocity at 1.0m/s and thickness slice at 4 mm



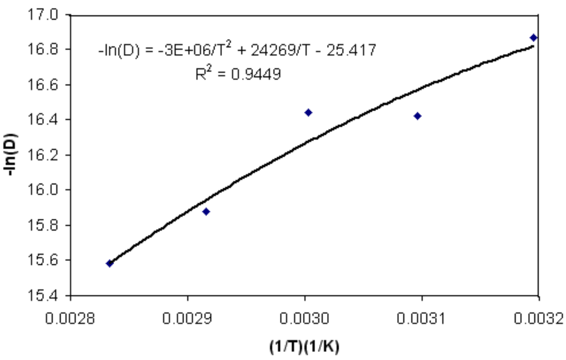
f- Air velocity at 2.0m/s and thickness slice at 4 mm



g- Air velocity at 0.5m/s and thickness slice at 6 mm



h- Air velocity at 1.0m/s and thickness slice at 6 mm



i- Air velocity at 2.0m/s and thickness slice at 6 mm

Fig 3. Arrhenius type relationship between effective diffusivity and temperature

to its steady state condition. Then, the tray holding the samples is carefully put in the dryer.

At first, a foreign Golab apple cultivar was selected. Being seedless makes the sliced product suitable for drying. Apples were washed, peeled and sliced in thicknesses of 2, 4 and 6 mm using a slicer machine. The uniform thickness of $t \pm 0.01$ mm was prepared by adjusting the opening of the slicer with a vernier caliper having a least count of 0.01 mm. About 150 g of apple slices were weighed and uniformly spread in a tray and kept inside the dryer. The apple moisture content of 4.9-6.3 gr water/gr dry solid was obtained by the oven method.

Results and discussion

Drying rates were calculated from the drying data by estimating the change in moisture content, which occurred in each consecutive time interval and in constant air humidity and was expressed as kg water/kg dry matter × min. For example, the variations of the drying rates as against moisture content are shown in Figure 2, for velocity of 0.5 m/s and thickness of 2 mm. As shown in Figure 2, the drying rate increased with increasing drying air temperature and reached its maximum values at 80°C. Drying rate decreased continuously with decreasing moisture content or increasing drying time in constant air humidity of 21%.

The accelerated drying rates may be attributed to internal heat generation. The absence of a constant drying rate period may be due to the thin layer of product that did not provide a constant supply of water in the specified period of time. Also, some resistance to water movement may exist due to shrinkage of the product on the surface, which reduces the drying rate considerably. The relationship between the drying rate and the moisture content was obtained by regression analysis. For temperature 40 °C and 50 °C the relationship was found to be linear while for 60 °C, 70 °C and 80 °C it was of the second degree polynomial form. Table 2 illustrates the linear and non-linear relationships between drying rate and moisture content obtained from regression analysis. The values for the coefficient of determination R^2 were in the range of 0.315-0.957. Results show that the thin layer drying of apple slices occurs entirely in the falling rate period. However, the drying rate appears to be slow and gradually receding for the low level of temperature and was observed to increase at higher levels (Figure 2). An increase in drying rates with an increase in temperature has been reported in earlier studies by Pathare and Sharma (Pathare and Sharma, 2006) for onion slice, Akpinar et al. (Akpinar et al., 2003) for red pepper slice, Mohapatra and Rao (Mohapatra and Rao, 2005) for parboiled wheat, Doymaz (Doymaz, 2005) for green bean, Madamba et al. (Madamba et al., 1996) for garlic slice.

The effective moisture diffusivity D was calculated using Eq. 5 and is shown in Table 3. The effective diffusivity values of dried samples at 40-80ºC were varied in the range of 1.50×10^{-8} and 1.71×10^{-7} m²/s. It can be seen that D values increased greatly with increasing temperature. Drying at 80ºC gave the highest D values. Based on the independent variables thickness (TK), drying air temperature and air velocity, using the multivariate regression technique (Eq. 6), the effective diffusivity with R^2 of 0.880 was estimated.

$$D = a + bTK + cV + dT \qquad (6)$$

where: a= -1.15553×10^{-7}, b= 1.53×10^{-8}, c= 4.55048×10^{-9}, d= 1.92733×10^{-9}

The relationship of the effective moisture diffusivity and temperature follows the Arrhenius equation, shown by Eq 2. The activation energy (Ea) and diffusion constant were determined from the slope of the Arrhenius plot, ln(D) vs. 1/T, and given in Table 4 and ln(D) as a function of reciprocal of absolute temperature (T) is plotted in Figure 3. Results show both linear and nonlinear relationships between ln(D) and (1/T).

The activation energy of all samples was less than 31000 J/mol, ranging from 22664.1 to 30919.0 J/mol, similar to values reported by several authors for different fruits and vegetables. For example, 23447-51081 J/mol in Wheat (Rafiee et al., 2008); 32940 J/mol for untreated tomato (Doymaz, 2007) and 24700-28400 J/mol in green peas (Simal et al., 1996). Activation energy of apple slice showed slightly higher compared to carrots (16000 J/mol) (Reyes et al., 2002) and lower than red chilli drying (41950 J/mol) (Gupta et al., 2002) and okra (51260 J/mol) (Doymaz, 2005).

Using the regression method, one can estimate ln(D) by knowing 1/T with high R^2 of 0.9449 to 0.9991. As can be seen from Figure 3, for 2mm thickness and air velocities of 0.5 m/s and 6mm thickness and air velocities of 2 m/s, the relationship is second degree polynomial while for the rest it is linear.

Conclusions

1- Effective moisture diffusivity increases with increase in drying air temperature and constant air humidity. The highest effective diffusion was found to be 1.71×10^{-7} m^2/s in air temperature, air velocity and slice thickness of 80ºC, 2 m/s and 6 mm, respectively. The lowest effective diffusion was 1.50×10^{-8} m^2/s in air temperature, air velocity and slice thickness of 40ºC, 0.5 m/s and 2 mm, respectively.

2- The highest activation energy value of apple slice was determined as 30919.0 J/mol at the slice thickness of 6 mm and drying air velocity of 2 m/s and the lowest value was 22664.1 J/mol at the slice thickness of 2mm and drying air velocity of 0.5 m/s.

3- The diffusion constant value of apple slice was attained as 6.34×10^{-3} m^2/s at the slice thickness of 6mm and drying air velocity of 2 m/s and the lowest value was 1.16×10^{-4} m^2/s at the slice thickness of 2mm and drying air velocity of 0.5 m/s.

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