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Effective Moisture Diffusivity and Activation Energy of Tomato in Thin Layer Dryer during Hot Air Drying

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ABSTRACT

The aim of this paper is to report tomato slice moisture diffusivity data determined and activation energy from experimental drying kinetics. The thin-layer drying experiments were carried out under five air temperatures of 40, 50, 60, 70 and 80°C, two air velocity 1.5, and 2 m/s and three level of relative humidity 20, 40 and 60%. It was observed that drying took place in the falling rate period. Moisture transfer from tomato slice was described by applying the Fick's diffusion model. The effective diffusivity values changed from 9.9119×10^{-10} to 6.4037×10^{-9} m^2/s for the range of temperatures considered. An Arrhenius relation with an activation energy value of 33.3299 to 43.2287 kJ/mol and the diffusivity constant value of 1.7695×10^{-4} to 3.09156×10^{-2} m^2/s were obtained which shows the effect of drying air temperature, air velocity and relative humidity on the diffusivity.

1. Introduction

The one of the most important methods for industrial food preservation is drying. Many applications of drying have been successfully applied to minimize biochemical, chemical and microbiological deterioration of food products due to the reduction of the moisture content to the level, which allows safe storage over a long period and brings substantial reduction in

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weight and volume, minimizing packaging, storage and transportation costs (Zielinska & Markowski , 2010).The objective of drying is the removal of water to a level at which microbial spoilage and deterioration reactions are greatly minimized (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 generalize 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 agriculture products such as heat and mass transfer, moisture diffusion, and energy of activation are required for ideal dryer design (Aghbashlo et al., 2008).

Thin-layer drying refers to the drying process in which all the products are fully exposed to the drying air under constant drying condition, i.e., at constant air temperature and humidity. Investigators have studied numerous researches about moisture diffusion and energy of activation on the thin layer drying of various agricultural products, such as seedless grapes (Doymaz & Pala 2002). Plum (Goyal et al. 2007), grapes (Pahlavanzadeh et al., 2001), candle nuts (Tarigan et al., 2006), potato slices (Akpinar et al., 2003), beriberi fruit (Aghbashlo et al., 2008), and onion slices (Pathare & Sharma 2006).

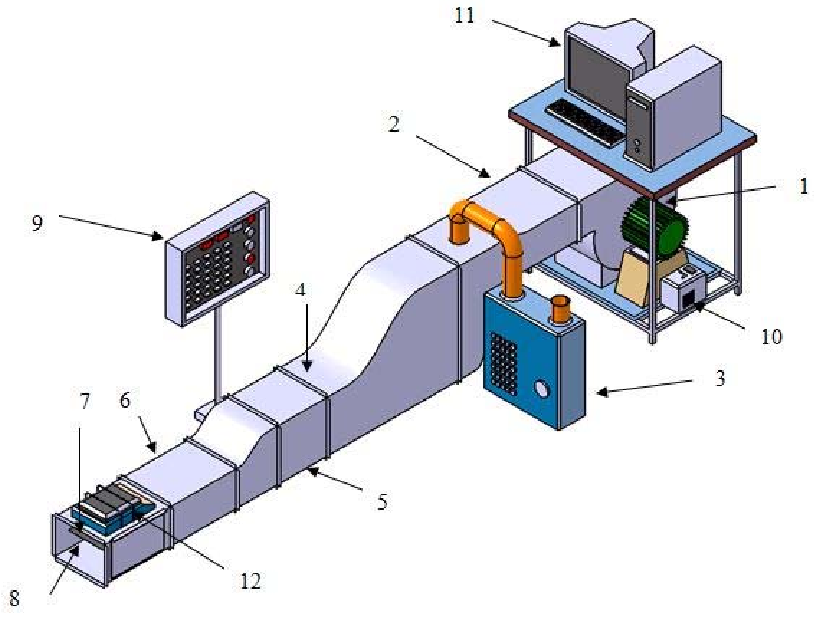

Figure 1: Pilot thin-layer drying

1-Fan 2- dehumidifier 3- humidifier 4- relative humidity sensor 5- heaters 6- Straightener 7- temperature sensor 8- Tray 9- control board 10- invertor 11- computer 12- digital balance

2. Materials and Methods

2.1 Samples Preparation and Drying Unit

Drying experiment was performed using pilot scale dryer which was designed and fabricated in the Department of Agricultural Machinery at University of Tehran (2011). A schematic diagram of this dryer is shown in Figure 1. A portable, 0-10 m/s range digital anemometer (TESTO, 405-V1) was used to measure passing air flow velocity through the system. The airflow was adjusted by a variable speed blower. The heating structure was consisted of ten heating elements placed inside the channel. Moreover, a simple control algorithm was used to control and adjust the drying tunnel temperature and relative humidity of air used for drying. 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. The used measuring instruments with their specifications are given in Table 1.

Table 1: Specifications of measurement instruments including their rated accuracy.

Instrument	Model	Accuracy	Manufacturer
Digital balance	GF3000	±0.02	A&D, Japan
T-sensor	LM35	$\pm 1^0$C	NSC, USA
RH-sensor	SHT15	±2%	CHINA
V-sensor	405-V1	±3%	TESTO, UK

The airflow control unit was regulated the velocity of the drying air flowing through the 30 cm diameter drying chamber. The dryer was capable of providing any desired drying air temperature in the range of 20 to 120 °C and air relative humidity in the range of 5 to 95% and air velocity in the range of 0.1 to 5.0 m/s with high accuracy. After turning on the computer, fan, scale, elements and data acquisition system, the essential velocity for the fan was set. The control software was implemented and the required temperature and relative humidity of air for the experiment were adjusted. Experiments were carried out 20 minutes after the system was turned on to reach its steady state condition. After that, the tray holding the samples was carefully put in the dryer. After that, the tray holding the samples was carefully put in the dryer. About 200 g of tomato were weighed and uniformly spread in a tray and kept inside the dryer. Three replications of each experiment were performed

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according to a pre-set air temperature and time schedule. The reproducibility of the experiments was within the range of ±5%. The hot air drying was applied until the weight of samples reduced to a level corresponding to moisture content of about 0.5% d.b. The drying experiment was conducted at five air temperatures of 40, 50, 60, 70 and 80°C and at three relative humidity 20%, 40% and 60% and air velocity of 1.5 and 2.0 m/s. The initial and final moisture contents of the tomato were determined at 78°C during 48 h with the oven method (AOAC, 1984).

2.2 Effective coefficient moisture diffusivity

Drying process of food materials generally occurs in the falling rate period (Wang & Brennan, 1992). To predict the moisture transfer during the falling rate drying period, several mathematical models have been proposed using Fick's second law. By using Fick's second law and considering following assumptions, proposed Eq. (1) for the effective moisture diffusivity for an infinite slab (Crank, 1975):

(1) Moisture is initially distributed uniformly throughout the mass of a sample.

(2) Mass transfer is symmetric with respect to the center.

(3) Surface moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air.

(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.

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

Where MR is moisture ratio, M is the moisture content at any time (kg water/kg dry mater), M_0 is the initial moisture content (kg water/kg dry solid), n = 1, 2, 3, . . . the number of terms taken into consideration, t is the time of drying in second, D is effective moisture diffusivity in m^2/s and L is the thickness of slice (m).

Only the first term of Equation (1) is used for long drying times (Lopez et al., 2000), hence:

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

The slope (k_0) is calculated by plotting ln(MR) versus time according to Eq. (3):

$$k_0 = \frac{\pi^2 D}{4L^2} \quad (3)$$

2.3 Energy of Activation

The energy of activation was calculated by using an Arrhenius type equation (Lopez et al., 2000; Akpinar et al., 2003):

$$D = D_0 \exp\left(-\frac{E_a}{RT_a} \right) \quad (4)$$

Where E_a is the energy of activation (kJ/mol), R is universal gas constant (8.3143 kJ/mol), Ta is absolute air temperature (K), and D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s).

The activation energy can be determined from the slope of the Arrhenius plot, ln(D) versus $1/T_a$.

From Eq. (4), a plot of Ln D versus $1/T_a$ gives a straight slope of K_1

$$K_1 = E_a / R \quad (5)$$

The linear regression analysis was performed using statistic computer program to fit the equation to the experimental data to obtain correlation coefficient (R^2).

The drying process was stopped after no further change in weights was observed. At this point moisture content decreased from 93.5 % to 15 % (w.b.).

3. Results and Discussion

Effective coefficient moisture diffusivity D calculated by Equation (4) is shown in Table (2). It is obvious that the effective distribution coefficient in samples which dried at temperatures between 40 to 80°C, are varied between from 9.9119×10^{-10} m^2/s to 6.4037×10^{-9}.

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It can be seen the minimum of effective coefficient moisture diffusivity is in the lowest temperature (40°C). While the maximum of effective coefficient moisture diffusivity is in the highest temperature (80°C). Overall effective coefficient moisture diffusivity rate for food product changes in the range of m^2/s from 10^{-11} to 10^{-9} (Bablis and Belessiotis 2004; Aghbashlo *et al*., 2008).

Table 2: Estimated effective moisture diffusivity in different condition of air dryer.

Air velocity (m/s)	Relative humidity (%)	Diffusion coefficient (m^2/s)				
		80^0C	70^0C	60^0C	50^0C	40^0C
1.5	20	5.8354×10^{-9}	3.7099×10^{-9}	2.6425×10^{-9}	2.2227×10^{-9}	1.4708×10^{-9}
2	20	6.4037×10^{-9}	3.5491×10^{-9}	2.4151×10^{-9}	1.736×10^{-9}	2.1556×10^{-9}
1.5	40	6.3449×10^{-9}	3.5673×10^{-9}	2.701×10^{-9}	1.7135×10^{-9}	1.2383×10^{-9}
2	40	5.2563×10^{-9}	3.2624×10^{-9}	2.2845×10^{-9}	1.54566×10^{-9}	1.221×10^{-9}
1.5	60	5.5372×10^{-9}	3.7127×10^{-9}	1.8525×10^{-9}	1.6652×10^{-9}	9.9119×10^{-10}
2	60	5.1497×10^{-9}	2.6688×10^{-9}	2.0918×10^{-9}	1.5291×10^{-9}	1.2667×10^{-9}

Table 3: Estimated activation energy and moisture diffusivity constant in different condition of air dryer

Relative humidity (%)	Air velocity (m/s)	D_0 (m^2/s)	E_a (kJ/mol)	R^2
20	1.5	1.7695×10^{-4}	33.3299	0.975
20	2	3.831×10^{-3}	37.5474	0.887
40	1.5	1.28765×10^{-3}	41.737	0.978
40	2	2.3563×10^{-4}	38.1615	0.986
60	1.5	3.09156×10^{-2}	43.2287	0.981
60	2	1.2208×10^{-3}	`39.6889	0.934

Calculations indicate that there is a direct relationship between temperature and the effective spread, which show the increase of temperature lead to increase of the effective distribution coefficient. Temperature 80°C has the highest value of D in different humidity and intake air speed conditions. Using the Arrhenius relationship which gained in equation 2, the dependence of effective coefficient moisture diffusivity to temperature described correctly. Activation energy and constant effective coefficient diffusivity are calculated from the slope of Arrhenius (Ln(D)-1/T) and are shown in table (3). Amplitude changes of effective coefficient moisture diffusivity for tomato were gained from 9.9119×10^{-10} to 6.4037×10^{-9} in the temperature range between 40 to 80°C. Activation energy of samples was less than 44 kJ/mol and the range of that it varied from 33.3299 to 43.2287 kJ/mol.

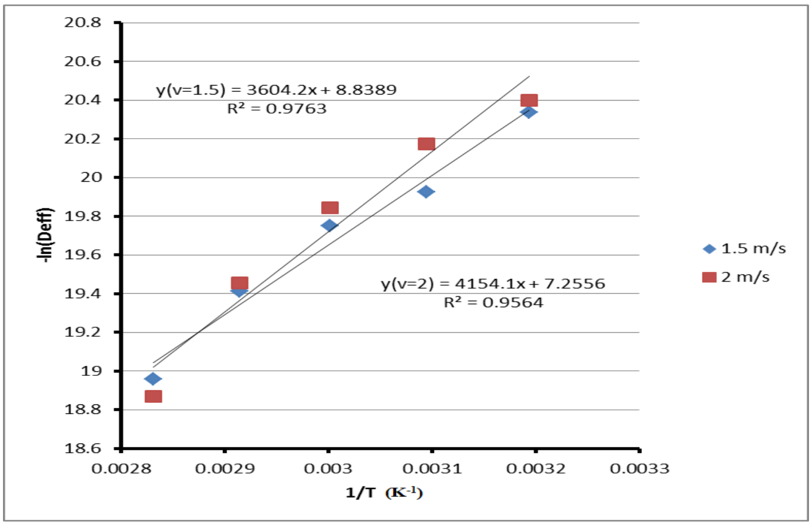

Figure 2: Relationship between effective coefficient moisture diffusivity and temperature for relative humidity of 20%.

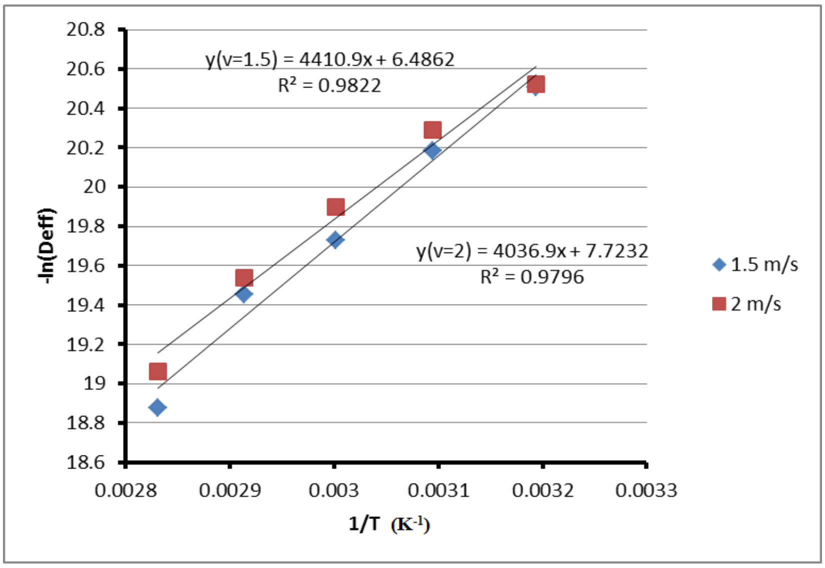

Figure 3: Relationship between effective coefficient moisture diffusivity and temperature for relative humidity of 40%.

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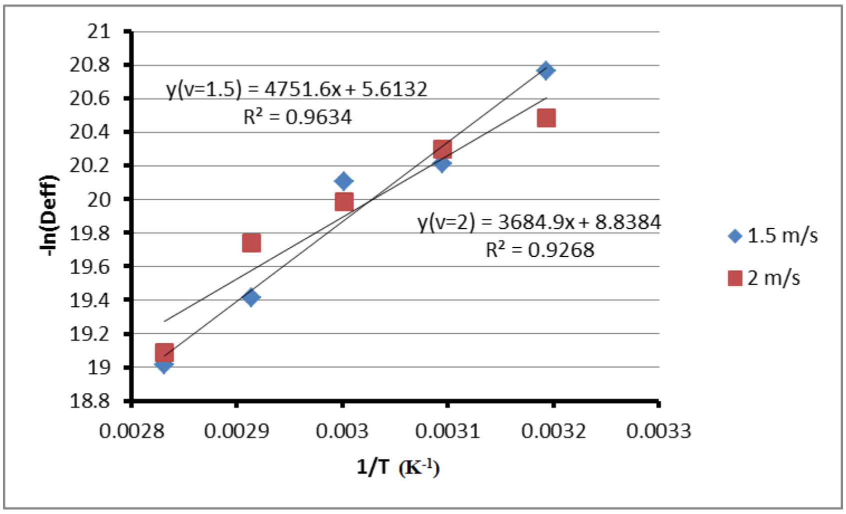

Figure 4: Relationship between effective coefficient moisture diffusivity and temperature for relative humidity of 60%.

With increasing relative humidity and increasing the air velocity of dryer reduction in activation energy is observed in Table 3. Relationship between effective coefficient moisture diffusivity and temperature is shown, by Figures 2 to 4 for different conditions. These figures were obtained via linear regression, the coefficient of determination (R^2) for the effective coefficient moisture diffusivity of correlation between temperature and humidity at three levels and three levels of air velocity was examined between from 0.9268 to 0.9822 achieved that highest value was obtained (0.9822) for air velocity of 1.5 m/s and relative humidity of 40%. In table 3, activation energy of samples was calculated less than 44 kJ/mol and the range of that it varied from 33.3299 to 43.2287 kJ/mol and the diffusivity constant value of 1.7695×10^{-4} to 3.09156×10^{-2} m^2/s were obtained which shows the effect of drying air temperature, air velocity and relative humidity on the diffusivity.

4. Conclusions

The effective coefficient moisture diffusivity is increasing with increases of drying temperature. In the study, the drying of tomato 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 6.4037×10^{-9} m^2/s at the air temperature of 80°C, relative humidity of 20% and air velocity of 2 m/s,. The lowest effective diffusion was 9.9119×10^{-10} m^2/s at the air temperature, relative humidity and air velocity of

40°C, 60% and1.5 m/s, respectively. It was deduced that at a low air velocity (0.5 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. Activation energy of samples was calculated less than kJ/mol 44 and the range of that it varied from 33.3299 to 43.2287 kJ/mol and the diffusivity constant value of 1.7695×10^{-4} to 3.09156×10^{-2} m^2/s were obtained which shows the effect of drying air temperature, air velocity and relative humidity on the diffusivity.

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