Dehydration Characteristics of Whole Lemons in a Convective Hot Air Dryer

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ABSTRACT: *In this study, whole lemons were dried using a laboratory convective hot air dryer and the effects of drying temperature on dehydration behaviour and mass transfer characteristics of the lemons were investigated. The drying experiments were conducted using air temperatures of 50, 60 and 75 °C and air velocity of 1 m/s. It was observed that the drying temperature affected the drying time and the drying rate significantly. Drying rate represented no constant period and the entire dehydration process took place in the falling rate period. The usefulness of five mathematical models to simulate the drying kinetics was evaluated and Midilli and logarithmic models were found as the best models describing the drying curves. The effective moisture diffusivity values were obtained to be* 1.15×10^{-10}, 2.29×10^{-10}, *and* 7.63×10^{-10} m^2/s *for the applied temperatures, respectively. The activation energy was also determined to be 71.32 kJ/mol. The convective mass transfer coefficient values were calculated by the analytical model and obtained to be* 4.078×10^{-7}, 1.023×10^{-7} *and* 4.346×10^{-8} *m/s for drying temperatures of 75, 60 and 50 °C, respectively.*

KEYWORDS: *Whole lemon; Drying behaviour; Moisture diffusivity; Mass transfer coefficient.*

INTRODUCTION

Drying is one of the significant unit operations in food processing industry [1]. This process plays an important role in easy and low cost packaging, handling, transport and safe storage of the materials [2]. In addition, the dried products have less volume, longer shelf life by slowing microorganism's growth and preventing certain biochemical

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reactions that might alter the organoleptic characteristics, and more popularity due to their diversity [3,4].

Open sun drying is the traditional method used to dry agricultural products that is simple and has low investment costs. However, this method poses some problems such as long drying time, dust and microbial contamination of the dried materials, and fluctuating quality of the dried products in a humid climate [5,6]. Hence, in order to reduce crop losses, improve the quality and reduce the process duration, industrial drying methods should be employed [7].

The drying process not only needs a great amount of energy, but also cause different changes in final product properties and the design of new dryers with minimum energy consumption and desired quality attributes remains a serious challenge [8,9]. To design novel dryers or improve the existing ones, and control the drying systems, mathematical models are used to model and simulate the drying process. The main proposed mathematical models used to describe the drying behaviour of agricultural materials include theoretical, semi-theoretical and empirical models. The major difference between these models is that only the internal resistance is considered by theoretical models, while semi-theoretical and empirical models account for only the external resistance. Theoretical simulations can give an explanation for phenomena occurring through drying process but, are more difficult and require a substantial amount of computing time. The empirical models neglect the fundamentals of drying process and derive a direct correlation between average moisture content and drying time. The semi-theoretical models are generally derived from direct solution of Fick’s second law and offer a compromise between theory and ease of application [7].

A literature review revealed that a large number of studies covering drying behaviour and mathematical modelling have focused on various agricultural products such as eggplant [10], rapeseed [11], golden berry [12], sweet potato [13], papaya [14], saffron [15] and pistachio nuts [16]. Nonetheless, to the best of our knowledge, drying of whole lemons has not been reported in the literature yet.

Lemon (*Citruslimon* (L.) Burm. f) is and acid citrus fruit grown in semi-arid and coastal areas with excellent quality and produced primarily for the fresh market with the juice being used as beverages [7]. In Iran, lemons are also dried in order to consume in food cooking and therefore, the development of a drying process is necessary. In 2011, Iran, with an annual production of about 560000 tonnes of lemon and lime, became the ninth producing country in the world after China, Mexico, India, Argentina, Brazil, United States, Turkey and Spain [17].

Convective hot air drying is the most widely used process to dehydrate food stuffs and is considered as simultaneous heat and mass transfer phenomena wherein the moisture content of the material is removed [6,18]. In this process, moisture transfer occurs in two forms of internal vapour evaporation and surface evaporation. Water is transferred from inside of the product to the air and product interface by diffusion and from the interface to the air stream by convection. Hence, effective moisture diffusivity and convective moisture transfer coefficient are two important parameters of mass transfer required for modelling and predicting the drying process [5]. These parameters are affected by drying method and conditions and physico-chemical properties of material, as well as moisture content [19].

The main objectives of this study were investigating the effect of temperature on drying behaviour of whole lemons in a convective hot air dryer, fitting the experimental data to five most used semi-theoretical models available in the literature, and determining the product mass transfer characteristics.

EXPERIMENTAL SECTION

Experimental set-up

A laboratory scale hot air dryer was used to carry out the drying experiments (Fig. 1). The dryer consisted of a centrifugal fan (2 hp three phase motor and the maximum speed of 2800 rpm), a heating chamber (ten 700 W electrical heating coils), a drying chamber (square chamber with a cross section of 40×40 cm), and an electronic controller unit (air velocity and temperature controllers). In the experiments, air was blown into the heater by the fan, heated up to the desired temperature and then passed to the drying chamber. The drying air temperature was measured in the drying chamber inlet by a thermometer (PT100, 0.1 °C resolution, Testo GmbH & Co., Lenzkirch, Germany) and controlled with the accuracy of ±0.1 °C by means of a temperature controller acting according to the increase/decrease in the electrical current to the heating elements. The drying air velocity

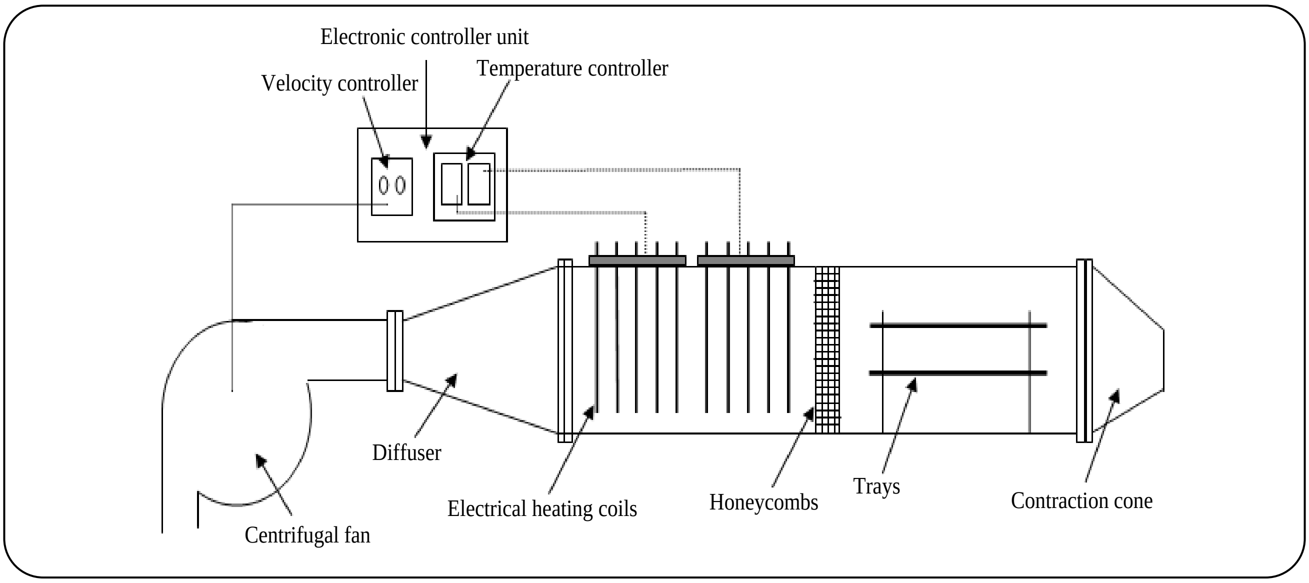

Fig. 1: A schematic view of the experimental set-up.

was measured by a hot wire anemometer (Lutron, AM-4204 model, with the accuracy of ±0.1 m/s, Lutron Electronic Enterprise Co., Ltd., Taipei, Taiwan) and adjusted by means of a 1 to 3 phase frequency inverter (TECO, 7300 CV, TECO Electric & Machinery Co. Ltd., Taipei, Taiwan).

Materials

Fresh lemons were purchased from a local market in Iafahan (central Iran), and stored in a refrigerator at 6 °C until the experiments were started. In order to determine the samples shape and the required dimensions for simulation, width, length and thickness of the fresh samples were measured using a digital calliper with the accuracy of 0.01 mm and then, the equivalent diameter and sphericity were calculated using Eqs. (1) and (2) [20].

$$d_e = (ABC)^{1/3} \tag{1}$$

$$\psi = \frac{(ABC)^{1/3}}{A} \tag{2}$$

Where *A*, *B* and *C* are the sample length (m), width (m) and thickness (m), respectively. Also, d_e is the sample equivalent diameter (m) and ψ is the sample sphericity. Average values of the equivalent diameter and sphericity were obtained to be 0.0384 m and 0.944, respectively. According to the obtained sphericity, each lemon was assumed to be a sphere with the radius of 0.0192 m.

Experiments

Prior to each drying experiment, the lemons were placed at room temperature for 24 h to reach thermal equilibrium with the environment. The average initial moisture content of the fresh samples was determined using vacuum drying at 70 °C, and obtained to be 6.14 kg H_2O/kg dry matter. The drying experiments were conducted at the temperatures of 50, 60 and 75 °C and a constant air velocity of 1 m/s. For each experiment, the dryer was run to reach steady state conditions for the set point (at least 20 min) and then, the samples (utilising 25 lemons in each batch with approximate weight of 1000 g) were placed uniformly on the drying tray. Using a digital balance (Sartorius 18100P with the accuracy of 0.01 g, Sartorius Co., Germany), continuous sample weighing was carried out during the drying and the instantaneous moisture content was computed using Eq. (3) [3]:

$$M = \left(\frac{(M_o + 1) \times W}{W_0} - 1 \right) \tag{3}$$

Where *M* and M_o are the moisture content at each time (kg H_2O/kg dry matter) and the initial moisture content (kg H_2O/kg dry matter), respectively. *W* and W_0 are the weight of the samples at each time (kg) and the initial weight of the fresh samples (kg), respectively.

The drying operation was continued until the samples batch was dried to the final moisture content of about 0.2-0.4 kg H_2O/kg dry matter.

Table 1. Mathematical models fitted to the experimental drying data.

Model name	Model expression
Newton	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Henderson and Pabis	$MR = a\exp(-kt)$
Logarithmic	$MR = a\exp(-kt)+b$
Midilli	$MR = a\exp(-kt^n)+bt$

Drying rate

Drying rate was calculated using Eq. (4) [21]:

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{4}$$

where *DR* is the drying rate (kg H_2O/kg dry matter. h), M_t and M_{t+dt} are the moisture contents at *t* and *t+dt* respectively, and *t* is the drying time (h).

THEORETICAL SECTION

Mathematical modelling of drying kinetics

Five semi-theoretical models widely used in the literature (Table 1) were selected to describe the drying behaviour of the samples. In these models, *MR* represents the moisture ratio, which is defined as follows [22]:

$$MR = \frac{M - M_e}{M_o - M_e} \tag{5}$$

where *MR* is the dimensionless moisture ratio and M_e is the equilibrium moisture content (kg H_2O/kg dry matter).

Since the equilibrium moisture content values were relatively small compared with the initial and instantaneous moisture content values, the moisture ratio was simplified to [23]:

$$MR = \frac{M}{M_o} \tag{6}$$

The selected models were fitted to the experimental drying curves using direct least square and the coefficients of the models were estimated under each drying condition. The fit goodness of the models was assessed based on coefficient of determination (R^2), root mean square error (*RMSE*) and Chi-square (χ^2). For the best fit, the R^2 had to be high and *RMSE* and χ^2 values had to be low. These parameters are defined as [5,12]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{n}\left(MR_{exp,i} - \overline{MR}\right)^2} \tag{7}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{\frac{1}{2}} \tag{8}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - Z} \tag{9}$$

Where $MR_{exp,i}$ is the *i-th* experimental moisture ratio, $MR_{pre,i}$ is the *i-th* predicted moisture ratio, $\overline{MR}$ is the average of all experimental moisture ratios, *N* is the number of the observations and *z* is the number of the constants.

Determination of effective moisture diffusion (D_{eff}) and activation energy (E_a)

Falling drying rate period of biological products is controlled by the mechanism of liquid and/or vapour diffusion [24]. By assuming isotropic behaviour for the samples with regard to the water diffusivity and negligible volume shrinkage of the materials, moisture movement during drying can be represented by Fick's second law of transient diffusion (Eq. (10)).

$$\frac{\partial M}{\partial t} = Div\left[D_{eff}\,(gradM)\right] \tag{10}$$

By assuming uniform moisture distribution, negligible external resistance and constant diffusivity, the analytical solution of Eq. (10) for different solid regularly shaped geometries has been given by Crank (1975). For a sphere, it is written as [22]:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-n^2\pi^2 D_{eff}\,t}{r^2}\right) \tag{11}$$

Where D_{eff} is the effective moisture diffusivity (m^2/s), *r* is the radius of the sphere (m) and *n* is the number of the terms considered for the Fourier series. In this study, the first five terms of the series were taken to calculate the samples effective moisture diffusivity.

By using simple Arrhenius equation [25] the effective moisture diffusivity was related with drying temperature as given below:

$$D_{eff} = D_o \exp\left(-\frac{E_a}{RT_{abs}}\right) \tag{12}$$

where D_o is the constant equivalent to the diffusivity at infinitely high temperature or Arrhenius constant (m^2/s), R is the universal gas constant (8.314×10^{-3} kJ/mol K), T_{abs} is the absolute temperature (K), and E_a is the activation energy (kJ/mol).

Eq. (12) was written in natural logarithmic form [25]:

$$\ln(D_{eff}) = \mathrm{Ln}(D_o) - \frac{E_a}{R}\left(\frac{1}{T_{abs}}\right) \tag{13}$$

Then, the activation energy was determined by plotting ln (D_{eff}) versus $1/T_{abs}$.

Determination of convective mass transfer coefficient (h_m)

To analyze mass transfer inside the samples assumed as a sphere object (Fig. 2) the following assumptions were made to write the three-dimensional transient mass transfer equation [3]:

1) Thermophysical properties of the material are constant.

2) Deformation or shrinkage of the material is negligible during the drying process.

3) Heat generation inside the moist object is negligible.

4) Radiation effects are negligible.

5) One or two dimensional equations are not enough due to the samples shape.

Under these assumptions, the three-dimensional mass transfer equation can be written as [3]:

$$\left(\frac{1}{r^2}\right)\left(\frac{\partial}{\partial r}\right)\left(r^2\frac{\partial M}{\partial r}\right) = \left(\frac{1}{D}\right)\left(\frac{\partial M}{\partial t}\right) \tag{14}$$

with the following initial and boundary conditions:

$$M(r,t) = M_o, \quad t = 0, \quad 0 \le r \le R \tag{15}$$

$$\frac{\partial M}{\partial r}(r,t) = 0, \quad t > 0, \quad r = 0 \tag{16}$$

$$-D\frac{\partial M}{\partial r}(r,t) = h_m(M_s - M_e), \quad t > 0, \quad r = R \tag{17}$$

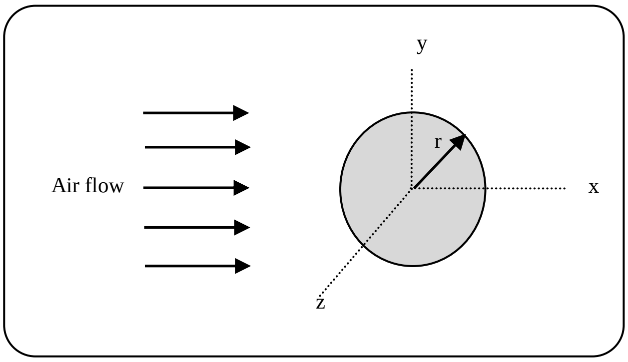

Fig. 2: The schematic of a whole lemon.

By using the procedure described by *Kaya et al.* (2007) [26], the convective mass transfer coefficient (h_m) in the surface of the lemons was determined. The convective mass transfer coefficient as a function of the moisture ratio (*MR*) and time is written as Eq. (15):

$$MR = \exp\left(-\frac{h_m S}{V} t\right) \tag{15}$$

where V and S are the sample volume (m^3) and the sample surface area (m^2), respectively.

For a symmetrically heated (or cooled) long cylinder or sphere, *V/S* is equal to the radius [27].

RESULTS AND DISCUSSION

Drying characteristics

Typical drying curves of the samples are presented in Fig. 3 for air temperatures of 50, 60 and 75 °C. These curves illustrate the variation of moisture content (kg H_2O/kg dry matter) *versus* time (h) during the process. As expected, the moisture content of the samples decreased continually. It was revealed that the drying temperatures had a significant effect on drying time ($p < 0.01$) and drying time decreased considerably when drying temperature increased. The required drying time to reach the final moisture content at the air temperatures of 50 (0.295 kg H_2O/kg dry matter), 60 (0.398 kg H_2O/kg dry matter) and 75 °C (0.251 kg H_2O/kg dry matter) was about 301, 127 and 38 h, respectively. The same results regarding the decrease in drying time with air temperature have been reported in the literature [27,28]. Drying duration of agricultural materials is dependent on some factors such as indigenous properties, initial and final moisture content of the product, drying method and drying conditions. At the higher temperatures, the heat

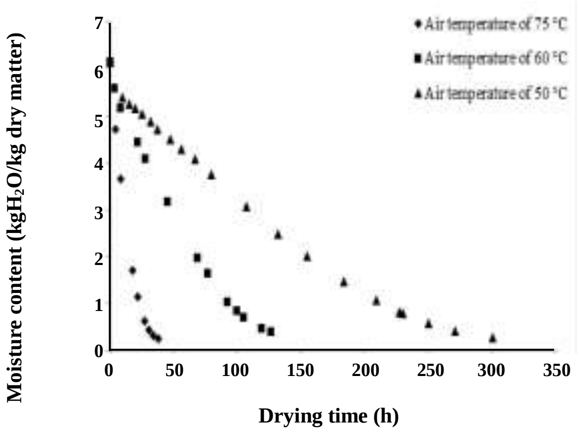

Fig. 3: Variation in moisture content with drying time for whole lemons at different applied air temperatures.

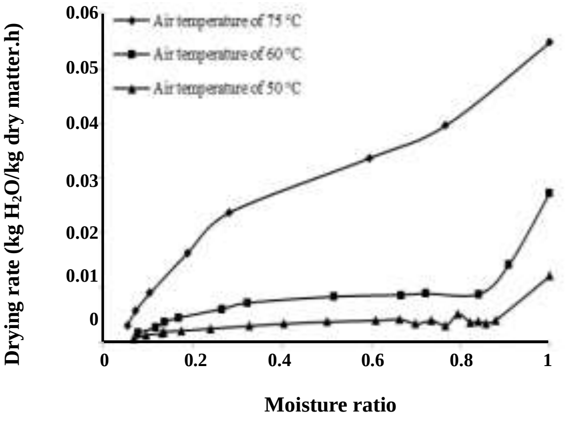

Fig. 4: Variation in drying rate with moisture content for whole lemons at different applied air temperatures..

transfer rate between thermal source and the material is higher, thereby leading to faster moisture evaporation and lower drying time. In spite of low drying time and consumed energy, high temperatures are not recommended for agricultural and food products due to damaging effects on physico-chemical properties of the dried materials.

Variations of drying rate as a function of moisture ratio at different drying temperatures are illustrated in Fig. 4. No constant rate period was observed in the drying process at all temperatures and the entire process took place in the falling rate period. This indicates that moisture movement in the whole lemons is governed by diffusion as the dominant physical mechanism. Also, drying rate was increased considerably with an increase in the drying air temperature where the average drying rate was 0.0036, 0.0085 and 0.0232 kg H_2O/kg dry matter. h at the temperatures of 50, 60 and 75 °C, respectively.

Modelling results

The five thin layer drying models mentioned in Table 1 were used to describe the drying process of whole lemons at three drying air temperatures. Table 2 represents the statistical analysis results for modelling. As shown, all the models yielded a R^2 greater than the acceptable R^2 value of 0.93 at all drying temperatures, but the highest R^2 values were obtained in the case of Midilli and logarithmic models. In addition, the lowest *RMSE* and Chi-square values were obtained for these models.

Effective moisture diffusivity and activation energy

By solving the first five terms in Eq. (11), the effective moisture diffusivity of the dried whole lemons was calculated and obtained to be 1.15×10^{-10}, 2.29×10^{-10} and 7.63×10^{-10} m^2/s for drying temperatures of 75, 60 and 50 °C, respectively. It is clear that the effective moisture diffusivity was increased considerably by an increase in drying temperature. An increase in the temperature decreases water viscosity and subsequently, resistance of fluid outflow. This leads to facilitating diffusion of water molecules in the product capillaries and finally, increasing moisture diffusivity value [29]. The obtained effective diffusivity values are in consistent with the values reported in the literature, e.g., 9.619×10^{-10} -1.556×10^{-9} m^2/s for hot air drying of oyster mushroom slices [30].

By plotting the natural logarithm of effective moisture diffusivity ($\ln D_{eff}$) *versus* the inverse of absolute temperature ($1/T_{abs}$), as shown in Fig. 6, and using Eq. (13), the values of D_o and E_a were calculated. Fig. 5 shows the linear relationship between ln D_{eff} and $1/T_{abs}$ with an R^2 value of 0.9964. The slope of the line is $-E_a/R$ and the intercept is equal to $\ln D_o$. The obtained activation energy (E_a) and Arrhenius constant (D_o) were 71.32 kJ/mol and 37.71 m^2/s, respectively.

Convective mass transfer coefficient (h_m)

The convective mass transfer coefficient was predicted from Eq. (15) via linear regression analysis and obtained to be 4.078×10^{-7}, 1.023×10^{-7} and 4.346×10^{-8} m/s

Table 2: The coefficient of the models under each drying condition along with the statistical analysis of the models.

Model	Drying temperature (°C)	Parameters	R^2	RMSE	χ^2
Newton	75	k= 0.073	0.9908	0.03402	0.001157
	60	k= 0.018	0.9868	0.03939	0.001552
	50	k= 0.008	0.9832	0.04166	0.001736
Page	75	k= 0.041, n= 1.201	0.9987	0.0135	0.000182
	60	k= 0.009, n= 1.161	0.9919	0.03234	0.001046
	50	k= 0.004, n= 1.127	0.9879	0.03622	0.001312
Henderson and Pabis	75	a= 1.158, k= 0.088	0.9920	0.05836	0.004379
	60	a= 1.118, k= 0.021	0.9867	0.06625	0.005188
	50	a= 1.138, k= 0.010	0.9712	0.07403	0.00606
Logarithmic	75	a= 1.114, b= -0.103, k= 0.059	0.9978	0.01916	0.000367
	60	a= 1.256, b= -0.2826,k= 0.011	0.9971	0.02017	0.000407
	50	a= 1.335, b= -0.373, k= 0.004	0.9966	0.01967	0.000387
Midilli	75	a= 0.995, b=-0.001, k= 0.043, n= 1.171	0.9990	0.01423	0.000202
	60	a= 0.970, b= -0.001, k= 0.0109, n= 1.046	0.9970	0.02186	0.000478
	50	a= 0.952, b= -0.001, k= 0.004, n= 1.084	0.9965	0.02068	0.00429

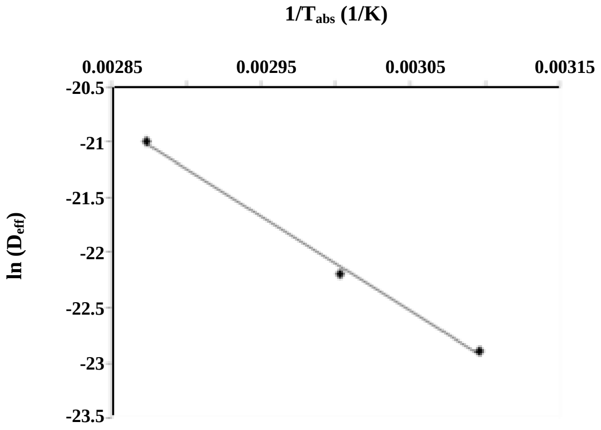

Fig. 5: Arrhenius type relationship between effective moisture diffusivity (D_{eff}) and temperature (T).

for drying temperatures of 75, 60 and 50 °C, respectively. These values agree well with the values reported in literature. *Kaya et al.* (2007) [26] determined the mass transfer coefficient values in the range of 5.140×10^{-7}-11.092×10^{-7} m/s for hot air drying of pumpkin at different air velocities and temperatures. *Kaya et al.* (2010) [28] evaluated the mass transfer coefficient for slab carrot as 1.947×10^{-7}-2.47×10^{-7} m/s and for spherical blueberry as 4×10^{-8}-7.1×10^{-7} m/s at drying air temperatures in the range of 30-60 °C and constant air velocity of 1 m/s.

CONCLUSIONS

To the best of authors' knowledge, based on literature reviewed, whole lemons were dried for the first time in this study. Drying conditions were selected as a constant drying air velocity of 1 m/s and three air temperatures of 50, 60 and 75 °C. Drying time was affected by drying air temperature significantly ($p< 0.01$), as the process duration for drying temperatures of 50, 60 and 75 °C was about 301, 127 and 38 h, respectively. Entire drying processes occurred in falling rate period and no constant rate period was observed. The Midilli and the logarithmic models were determined as the best models describing the drying kinetics according to the highest correlation coefficient and the lowest Chi square and *RMSE*. The effective moisture diffusivity values varied from 11.15×10^{-10} to 7.63×10^{-10} m^2/s for the applied drying temperatures. The activation energy was determined to be 71.32 kJ/mol. The convective mass transfer coefficients in the surface of the lemons were also in the range of 4.346×10^{-8} to 4.078×10^{-7} m/s for the air temperatures.

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