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# Effect of Different Drying Conditions on the Mass Transfer Characteristics of Kiwi Slices

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## ABSTRACT

**In this study, the influences of drying conditions on the mass transfer characteristics of kiwi slices are investigated using the analytical model proposed by Dincer and Dost. The experiments were conducted at temperature range of 50–80°C with 0.5 m $s^{-1}$ air velocity for convective drying and in the microwave power range of 200–500W for microwave drying as single layers with sliced thickness of 3, 6, and 9 mm. The results show that the mass transfer characteristics strongly depend on the drying conditions. Through the convective drying method, parameters including moisture diffusivity, mass transfer coefficient, Biot number, and drying time were varying from 0.16-1.45×$10^{-8}$ $m^2$ $s^{-1}$, 1.93-4.95×$10^{-7}$ m $s^{-1}$, 0.103-0.225, and 90-604 minutes, respectively. In comparison, for microwave drying, they were within the ranges of 0.66-25.60×$10^{-8}$ $m^2$ $s^{-1}$, 0.62-5.64×$10^{-5}$ m $s^{-1}$, 0.960-1.742, and 4-23.5 minutes, respectively. Results reveal that the activation energy for moisture diffusion is higher than that needed for the convective mass transfer process.**

**Keywords:** Activation energy, Analytical modeling, Drying method, Moisture diffusivity.



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## INTRODUCTION

Because kiwifruit has a very short shelf life due to its high moisture content (above 80% wet basis), it is necessary to use various preservation methods to increase its shelf life. Drying is among the suggested options for extending their short life, safe storage, easy packaging and transport, and improving economic value (Raquel *et al*., 2012; Kaya *et al*., 2010). Drying is a complicated process in which simultaneous heat and mass transfer phenomena, particularly under transient conditions, occur between a moist object and heat source, leading to vaporization of the object water.

The rate of mass transfer is a function of external mass transfer coefficient, activation energy, and mass diffusivity of water (McMinn *et al*., 2003; Kaya *et al*., 2010). The mass transfer parameters generally depend on drying conditions such as the mechanism of heat transfer (convection, conduction or radiation), thickness of layer, air relative humidity around the product, temperature of the product, airflow velocity, and type of product (Kaya *et al*., 2008; Darvishi *et al*., 2015; Bezerra *et al*., 2015). Determining the exact parameters of mass transfer is an essential factor to design new dryers, control the drying systems, reduce energy consumption, and improve the product quality (Bezerra *et al*., 2015; Beigi, 2015; McMinn *et al*., 2003). Kaya *et al*. (2008) established the heat and mass transfer analysis during convective drying of kiwi fruits using the commercial CFD analyses and obtained a considerably high agreement

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between numerical results and experimental data. Simal *et al*. (2005) found that the color and functional properties of the dried kiwi slices were mainly affected by the drying temperature and stage of fruit ripeness, respectively.

Darıcı and Sen (2015) showed that the Midilli model describes the experimental data adequately for convective drying of the kiwi slice. Jafari *et al*. (2015) conclude that reflectance window drying method is able to produce dried kiwifruit slices of high quality compared with oven drying method. Azizi *et al*. (2017) used several models to define their experimental data for reflectance window drying of kiwifruit slices and concluded that the Logarithmic model gives the best fit among them. Ayadi *et al*. (2014) reported that dried kiwi in the open-air sun drying method has high physicochemical properties as compared with microwave drying. The low temperature, high air velocity, and low distance between jet nozzles and material steel wire mesh box led to processing high-quality dried kiwifruit and reducing the energy consumption in heat pipe dryer combined with impingement technology (Li *et al*., 2016).

Although there are many studies in the literature on the investigation of the drying behavior of kiwifruits, the focus of these studies is on the quality aspects, mathematical modeling of drying curves using the empirical or semi-theoretical models, and calculation of moisture diffusivity based on theoretical Fick's diffusion technique. The theoretical solution of Fick's second law neglects the external mass transfer resistance within solid materials and is established on the basis of the internal mass transfer, while the analytical model considers both the internal and external resistances to moisture transfer within the solid (Guillard *et al*., 2004; Torki-Harchegani *et al*., 2015; Bezerra *et al*., 2015).

Torki-Harchegani *et al*. (2015) showed that the moisture diffusivity values estimated by the analytical Dost and Dincer model are greater (5.98 to 8.11-fold) than those obtained by the theoretical Fick's second law. This difference in diffusivity values could be partially explained by the significant influence of an external resistance to moisture transfer (Guillard *et al*., 2004). Also, previous studies have shown that the analytical Dost and Dincer model has high performance in determining the mass transfer parameters of biomaterials compared to the theoretical Fick's diffusion law (Bezerra *et al*., 2015; Beigi, 2015; Torki-Harchegani *et al*., 2015; Haghi and Amanifard, 2008).

Therefore, the aim of the present work was to: (1) Determine the mass transfer characteristics of kiwi slices, namely, moisture diffusivity, moisture transfer coefficient, activation energy, and Biot number using the analytical model proposed by Dincer and Dost, (2) Investigate the effect of different drying conditions such as air temperature, microwave power, and slice thickness on mass transfer characteristics, and (3) Evaluate the mathematical model capability to describe the drying curves by comparing the theoretically obtained dimensionless moisture ratio variations with the experimental data.

## MATERIALS AND METHODS

### Sample Preparation

Fresh kiwifruits (Mass: 64.40±3.72 g; Length: 57.47±3.17 mm; Width: 45.44±1.44 mm, Thickness: 41.54±1.46 mm) were purchased from a local market, cleaned with tap water, and then sliced in three different thicknesses of 3, 6, and 9 mm using a cutting machine. The initial average moisture content of samples was measured to be 83.5±1% (wet basis) or 5.08±0.05 (kg water $kg^{-1}$ dry matter).

### Drying Procedure

#### Convective Dryer

Pictures of the convective experimental apparatus are shown in Figure 1. The dryer consists of an electrical fan, electrical heater

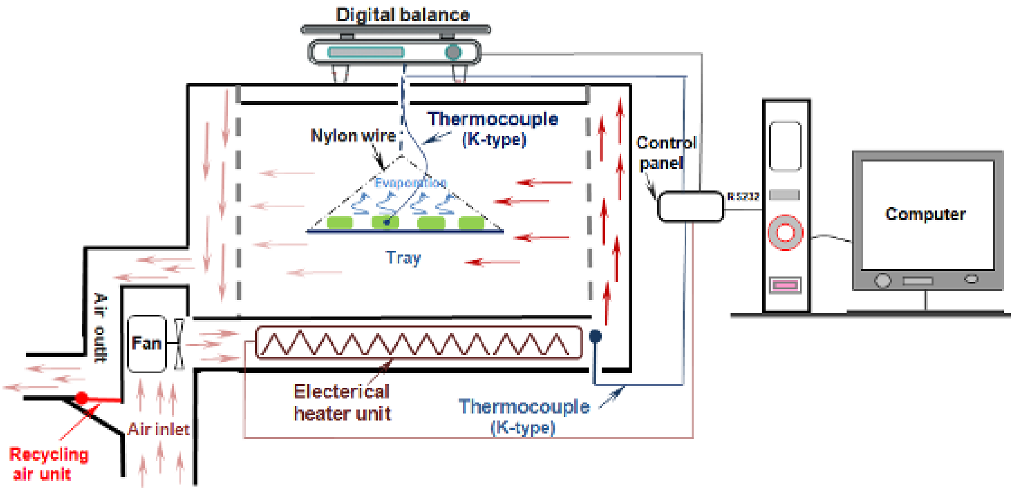


**Figure 1.** Schematic diagram of hot air convective drying system.

(4kW), drying chamber, control panel, and instruments for measurement. The temperature and airflow rate of drying chamber were adjusted by the heater power and fan speed controls, respectively. Properties of devices used in the study are given in Table 1. About 21±0.5 g of kiwi slices after weighing was uniformly spread on a tray and kept inside the dryer (Figure 1). The weight loss was recorded for 30 minutes using a digital balance (GF-600, A and D, Japan) with an accuracy of 0.01 g. The experiments were performed at drying temperatures varying from 50 to 80°C with 10°C increments and a constant air velocity of 0.5 m $s^{-1}$ until reaching a final moisture content of 10±1.5% (wet basis). Before each experiment, the temperature and velocity of the drying air were fixed and measured directly in the drying chamber without the sample. The experimental system was operated at ambient moisture conditions; i.e., the average room air condition of 18.5±1°C and relative humidity of 41.3±2.5% as measured by a humidity meter (Model: YK-90HT, Lutron, Taiwan). Drying process was stopped when the moisture content of the samples was about 10±1% (wet basis). The moisture content at any time in the drying experiment was calculated using the following equations (Jafari *et al*., 2016; Torki‐ Harchegani *et al*., 2015):

$$M_t = \left( \frac{(1+M_0)\times m_0}{m_t} - 1 \right) \qquad (1)$$

## Microwave Dryer

Schematic diagram of microwave dryer is depicted in Figure 2. Microwave drying experiments were carried out in a domestic digital microwave oven (M945, Samsung Electronics Ins) with the technical features

**Table 1.** Properties of devices used in the study.

| Device | Brand | Model | Range |
|---|---|---|---|
| Anemometer/Hot wire | Lutron | AM-4204 | 0.2 -20.0 (m $s^{-1}$) |
| Thermometer | Lutron | TM-917 | -100 –1370 (ºC) |
| Humidity meter | Lutron | HT-3009 | 0 to 100 (%RH) |
| Digital balance | A and D | GF-600 | -600–600 (g) |
| Microwave oven | Samsung | M945 | 0 –1000 (W) |
| Centrifugal fan | | Backward-urved | 0 – 2800 ($m^3$ $h^{-1}$) |
| Electrical heater | | | 0- 4 (Kw) |

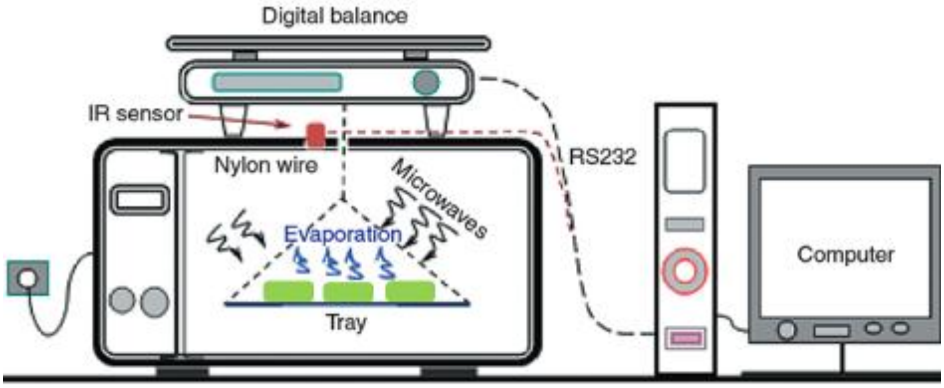


**Figure 2.** Schematic diagram of microwave drying system.

of 230V, 50 Hz, and 1,000W. The oven was able to work at various microwave outputs and had a digital control facility into adjusting the processing time. The moisture from oven chamber was removed with magnetron fan by passing it through the openings on the right side of the oven wall to the outer atmosphere. Mass loss of samples with an initial load of 21±0.5 g was recorded at 30 s intervals. To measure drying data during the drying process, a digital balance (GF-600, A and D, Japan) in the measurement range of 0–600 g and a precision of 0.001 g was used. Drying experiments were conducted at microwave power levels of 200, 300, 400, and 500W and slice thicknesses of 3, 6, and 9 mm with three replications. The experimental system was operated at ambient conditions; i.e. average room air conditions of 19±1.5℃ and 39±2% relative humidity. Drying process was stopped when the moisture content of the samples was about 10±1.5% (wet basis).

## Theory of Modeling

In this study, the Dincer and Dost model was applied to determine the mass transfer characteristics of the kiwi slices drying. The main reason for choosing this model was the high-performance of the model (reported by other researchers) for estimation of mass transfer coefficients of fruits and vegetables (Akpinar and Dincer, 2005; Bezerra *et al*., 2015; McMinn *et al*., 2003; Torki-Harchegani *et al*., 2015). Dincer and Dost (1996) presented a solution for the time-dependent diffusion equation for different geometric shaped moist objects. The transient moisture diffusivity equation for an infinite slab can be written as (Bezerra *et al*., 2015):

$$\frac{\partial}{\partial x}\left(D_m \frac{\partial M}{\partial x}\right) = \frac{\partial M}{\partial t} \qquad (2)$$

With the following initial and boundary conditions (Akpinar and Dincer, 2005):

$$M(x\ ,\ 0) = M_0 \quad and \quad \frac{\partial M}{\partial t}(0\ ,\ t) = 0 \qquad (3)$$

$$-D_m \frac{\partial M\left(\frac{L}{2},t\right)}{\partial x} = h_m\left[M\left(\frac{L}{2},t\right) - M_e\right] \qquad (4)$$

Solving Equation (2) with the boundary conditions yields a dimensionless center moisture distribution as follows (Bezerra *et al*., 2015; Beigi, 2015):

$$MR = \sum_{n=1}^{\infty} A_n B_n \qquad (5)$$

Where, *MR*, $A_n$, and $B_n$ are defined as follows:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \qquad (6)$$

$$A_n = \frac{2\sin(\mu_n)}{\mu_n + \sin(\mu_n)\cos(\mu_n)} \qquad 0.1 < Bi < 100 \qquad (7)$$

$$B_n = \exp\left(-\mu_n^2 F_o\right) \qquad Bi > 0.1 \qquad (8)$$





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The equilibrium moisture content of kiwi slices is equal to zero during microwave and convective drying. (Darıcı and Sen, 2015; Darvishi *et al*., 2016). For negligibly small values of Fourier number, Equation (5) can be simplified to the first term only (Torki-Harchegani *et al*., 2015; Beigi, 2015):

$$\mathrm{MR} = \mathrm{A}_1\,\mathrm{B}_1 \qquad (9)$$

Where:

$$\mathrm{A}_1 = \exp\left(\frac{0.2533\,\mathrm{Bi}}{1.3+\mathrm{Bi}}\right) \quad \text{for slab}-\text{shaped} \qquad (10)$$

$$B_1 = \exp\left(-\mu_1^2\,F_o\right) \qquad (11)$$

The moisture ratio can be expressed in exponential form as:

$$MR = G\exp\left(-S\,t\right) \qquad (12)$$

In Equation (11), Fourier number is defined as:

$$F_o = \frac{D_m \times t}{\left(\frac{L}{2}\right)^2} \qquad (13)$$

Equations (7) and (12) are in the same form and can be equated to each other by having $G= A_1$. Therefore, the moisture diffusivity is calculated as:

$$D_m = \frac{S \times \left(\frac{L}{2}\right)^2}{\mu_1^2} \qquad (14)$$

In Equation (14), $\mu_1$ can be calculated with respect to *Bi* for slab geometry using the following simplified expression (McMinn *et al*., 2003):

$$\mu_1 = a\tan\left(0.64044Bi + 0.38039\right) \qquad (15)$$

The mass transfer coefficient and the moisture diffusivity are correlated by the *Bi*, as follows (Beigi, 2015):

$$h_m = \frac{Bi \times D_m}{\left(\frac{L}{2}\right)} \qquad (16)$$

The relationship between the effective diffusivity, mass transfer coefficient, and the temperature is assumed in the Arrhenius form of the type (Raquel *et al*., 2012):

$$D_m = D_0 \exp\left(-\frac{E_{ad}}{R\left[T+273\right]}\right) \qquad (17$$

$$h_m = h_0 \exp\left(-\frac{E_{am}}{R\left[T+273\right]}\right) \qquad (18)$$

The dependence of the moisture diffusivity and mass transfer coefficient with microwave density ($P/m_0$) is assumed to be modifying Arrhenius function of the type (Özbek and Dadali, 2007):

$$D_m = D_0 \exp\left(-m_0\,\frac{E_{ad}}{P}\right) \qquad (19)$$

$$h_m = h_0 \exp\left(-m_0\,\frac{E_{am}}{P}\right) \qquad (20)$$

The procedure of using the above modeling technique for estimating the process parameters and drying parameters is as follows:

►The dimensionless values of moisture ratio and drying time were regressed in the exponential form of Equation (12) using the least square curve-fitting method. Hence, the values of lag factor (G) and drying coefficient (S) were determined.

► The *Bi* is calculated through Equation (10) since $G= A_1$.

►The value of $\mu_1$ was determined from Equation (15).

►The moisture diffusivity and moisture transfer coefficient are calculated from Equations (14) and (16).

## Uncertainty analysis

The uncertainty analysis is necessary to prove the accuracy of the experiments. During measurement and calculation of the parameters, the involved uncertainties were determined using the following equation and presented in Table 2.

$$W = \left(\left(\frac{\partial F}{\partial y_1}w_1\right)^2 + \left(\frac{\partial F}{\partial y_2}w_2\right)^2 + \cdots + \left(\frac{\partial F}{\partial y_n}w_n\right)^2\right)^{0.5} \qquad (21)$$





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**Table 2.** Uncertainties in the measurement and calculation of parameters during drying of kiwi slices.

| Description | Unit | Estimated uncertainty |
|---|---|---|
| Mass loss measurement | g | ±0.5 |
| Moisture quantity measurement | g | ±0.0141 |
| Drying time measurement | s | ±0.141 |
| Drying air velocity measurement | m $s^{-1}$ | ±0.17 |
| Temperature measurement | °C | ±0.02 |
| Relative humidity of air | % | ±0.141 |
| Moisture ratio | % | ±0.51 |
| Biot number | % | ±0.51 |
| Moisture diffusivity | % | ±0.1-0.2 |
| Mass transfer coefficient | % | ±0.51 |
| Uncertainty in reading values of table | % | ±0.1-0.2 |

### Statistical Analysis

All experiments were repeated three times and the average of the moisture content at each value was used for calculating the drying data. The results were compared in order to analyze the effect of air temperature, microwave power, and slices thickness on the selected properties using ANOVA and post hoc (Duncan) tests at the 5% significance level ($p \leq 0.05$). The statistical evaluation was performed using software SPSS V.13. Three criteria parameters, namely, $R^2$, $\chi^2$, and *RMSE* were calculated to determine the model performance.

## RESULTS AND DISCUSSION

### Constants and Applicability of the Model

The values of the constants of a mathematical model, $MR= G\ exp(-S.t)$, and the results of their statistical analysis for convective and microwave drying of kiwi slices are summarized in Tables 3 and 4. As shown in these Tables, $R^2$, $\chi^2$, and *RMSE* values vary from 0.968 to 0.988, 0.00112 to 0.00498, and 0.03000 to 0.05632 for convective drying, respectively, and from 0.930 to 0.986, 0.00119 to 0.00950, and 0.03384 to 0.09197 for microwave drying, respectively. From these data, it can be seen

**Table 3.** Drying coefficients and lag factors for convective drying of kiwi slices.

| *L* (mm) | *T* (ºC) | Model coefficients | | Statistical parameters | | |
|---|---|---|---|---|---|---|
| | | *G* | *S* | $R^2$ | $\chi^2$ | *RMSE* |
| 3 | 50 | 1.031 | 0.0091 | 0.987 | 0.00142 | 0.03375 |
| 3 | 60 | 1.027 | 0.0127 | 0.981 | 0.00279 | 0.04573 |
| 3 | 70 | 1.023 | 0.0182 | 0.976 | 0.00420 | 0.05291 |
| 3 | 80 | 1.019 | 0.0253 | 0.983 | 0.00376 | 0.04747 |
| 6 | 50 | 1.035 | 0.0051 | 0.982 | 0.00274 | 0.04422 |
| 6 | 60 | 1.032 | 0.0072 | 0.980 | 0.00498 | 0.05464 |
| 6 | 70 | 1.027 | 0.0094 | 0.985 | 0.00435 | 0.04661 |
| 6 | 80 | 1.024 | 0.0123 | 0.988 | 0.00162 | 0.03488 |
| 9 | 50 | 1.0381 | 0.0034 | 0.968 | 0.00423 | 0.05631 |
| 9 | 60 | 1.0350 | 0.0058 | 0.973 | 0.00476 | 0.05632 |
| 9 | 70 | 1.0293 | 0.0079 | 0.986 | 0.00314 | 0.04343 |
| 9 | 80 | 1.0271 | 0.0086 | 0.987 | 0.00112 | 0.03000 |





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**Table 4.** Drying coefficients and lag factors for microwave drying of kiwi slices.

| *L* (mm) | *P* (W) | Model coefficients | | Statistical parameters | | |
|---|---|---|---|---|---|---|
| | | *G* | *S* | $R^2$ | $\chi^2$ | *RMSE* |
| 3 | 200 | 1.140 | 0.1458 | 0.950 | 0.00537 | 0.07078 |
| 3 | 300 | 1.137 | 0.2502 | 0.948 | 0.00604 | 0.07325 |
| 3 | 400 | 1.125 | 0.3090 | 0.937 | 0.00856 | 0.08566 |
| 3 | 500 | 1.114 | 0.4367 | 0.935 | 0.00950 | 0.08717 |
| 6 | 200 | 1.156 | 0.1405 | 0.958 | 0.00463 | 0.06586 |
| 6 | 300 | 1.141 | 0.1868 | 0.930 | 0.00930 | 0.09197 |
| 6 | 400 | 1.132 | 0.3416 | 0.956 | 0.00568 | 0.06979 |
| 6 | 500 | 1.116 | 0.4181 | 0.949 | 0.00698 | 0.07557 |
| 9 | 200 | 1.147 | 0.1395 | 0.986 | 0.00119 | 0.03384 |
| 9 | 300 | 1.133 | 0.2476 | 0.980 | 0.00217 | 0.04448 |
| 9 | 400 | 1.123 | 0.3537 | 0.968 | 0.00395 | 0.05820 |
| 9 | 500 | 1.114 | 0.4651 | 0.963 | 0.00518 | 0.06512 |

that the selected model, $MR= G\ exp(-S.t)$, gives an adequate fit of statistical analysis results. Because *G* values are higher than 1 (Tables 3 and 4), the *Bi* is in the range of 0.1 to 100, indicating the presence of external and internal resistance to mass diffusivity (Bezerra *et al*., 2015). The statistical results showed that the microwave power, air temperature, and slice thickness had a significant effect on drying rate constant ($p\leq 0.05$).

The trend of drying rate constant for each drying method is shown in Figure 3. As expect, drying rate constant increased with the increasing air temperature and microwave power and decreasing slice thickness. This observation is explained by an increase in temperature and microwave power and a decrease in slice thickness of kiwi samples that leads to an increase in heat and mass transfer between the fluid and solid object and, consequently, a higher drying capability of the object (Darvishi *et al*., 2015). However, the slice thickness is less effective than the other two parameters (T and P) on the drying rate constant. The drying rate constant values for convective drying of kiwi slice vary between 0.0034 and 0.0253 ($\text{min}^{-1}$) while it varies between 0.1395 and 0.4367 ($\text{min}^{-1}$) for the kiwi microwave drying. As the results show, drying rate constant of kiwi slices in microwave drying is 16- to 54-fold higher than the convective drying rate constant. Such a difference can be explained by the heat transfer mechanism. Due to the low thermal conductivity of the material and the small contact area between the material and hot air, the rate of heat transfer in convective drying process decreases and causes a low mass transfer rate. Nevertheless, the quick energy absorption in microwave drying (heat

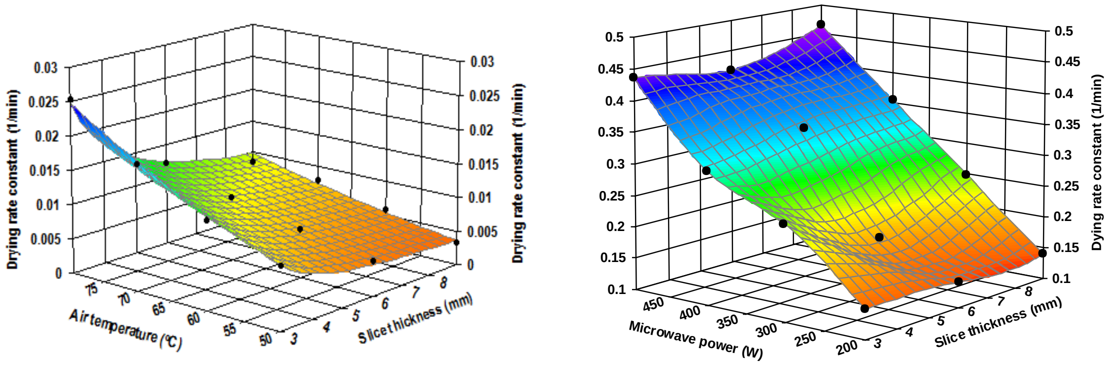


**Figure 3.** Variation of drying rate constant with drying conditions.

is generated within the food material by reorientation of the dipoles which in turn cause molecular friction) causes rapid evaporation of water. As a result, an outward flux of rapidly escaping vapor is created and both thermal gradient and moisture gradient are aligned in the same direction.

Drying rate constant ($min^{-1}$) against drying conditions is presented as follows:

$$S_{con} = 5.50\times10^{-7}\,T^{2.13}\ \exp\left(\frac{4.135}{L}\right)$$
$$R^2 = 0.991 \qquad (22)$$

$$S_{mic} = 1.94\times10^{-4}\,P^{1.24}\ \exp\left(\frac{L^{2.5}}{2975}\right) \qquad (23)$$
$$R^2 = 0.977$$

The comparisons between the experimental and the calculated moisture ratio distributions for different drying conditions are presented in Figure 4. As shown in this figure, the Dincer and Dost model provides a good agreement between experimental and predicted moisture ratio values. The same result is also reported in the literature about the capability of the model to predict the drying curves of different fruits and vegetables (Beigi *et al*., 2015; Torki-Harchegani *et al*., 2015; Sadeghi *et al*., 2013).

## Biot Number

The values of *Bi* and the first root of the transcendental characteristic equation for different drying conditions are presented in Table 5. The *Bi* values of microwave and convective drying ranged between 0.960-1.742 and 0.1032-0.2251, respectively. Values obtained for *Bi* of microwave drying is higher (about 6.18 to 9.36-fold) than those for the convective drying. According to the definition of Bi (the ratio of the internal resistance to mass transfer in the solid to the external resistance to mass transfer in the fluid), it can be stated that in the microwave drying method the effect of the external resistance to mass transfer is much smaller than that of the internal resistance; thus, the Bi will be high. Our results also showed that Bi decreased with increasing microwave power, air temperature, and slice thickness. When samples were dried at higher power or drying air temperature, the increased heating energy would increase the activity of water molecules resulting in higher mass transfer rate (Darvishi *et al*., 2015; Akpinar and Dincer, 2005). Finally, the effect of internal resistance in the mass transfer process and, consequently, Bi was reduced. However, the effect of slices thickness on the convective Bi was higher than that of the air temperature ($p< 0.05$). Also, microwave power had a stronger effect than that of the slice thickness on the variation in Bi of kiwi slices. The Bi for convective and microwave drying of the kiwi slice are presented by the following equations:

$$Bi_{con} = 0.311 + 0.043\ln(L) - 6.48\times10^{-3}T^{0.5}\ln(T)$$
$$R^2 = 0.990 \qquad (24)$$

$$Bi_{mic} = 1.46 + 0.185\,L - 0.015\,L^2 - 1.92\times10^{-3}P$$
$$R^2 = 0.946 \qquad (25)$$

## Moisture Diffusivity

As can be seen in Figure 5, the moisture diffusivity increased progressively with the increase in drying air temperature and applied microwave power ($p\leq 0.05$). This observation might be explained by the increased heating energy which can accelerate the water molecules present in the samples to evaporate faster and, thus, providing a faster decrease in the material moisture content and the corresponding higher value of effective moisture diffusivity (Darvishi *et al*., 2016; Sadeghi *et al*., 2013). Values of $D_m$ varied between $6.67\times10^{-9}$ (3 mm-200W) and $2.56\times10^{-7}$ $m^2$ $s^{-1}$ (9 mm-500W) for microwave drying, $1.62\times10^{-9}$ (3 mm- 50°C) and $1.45\times10^{-8}$ $m^2$ $s^{-1}$ (9 mm-80°C) for convective drying of kiwi slices





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**Table 5.** Mass transfer characteristics for microwave and convective drying of kiwi slices.

| L (mm) | Microwave drying | | | Convective drying | | |
|---|---|---|---|---|---|---|
| | P (w) | $\mu_1$ | Bi | T (ºC) | $\mu_1$ | Bi |
| 3 | 200 | 0.9052 | 1.395 | 50 | 0.4593 | 0.1781 |
| 3 | 300 | 0.8906 | 1.336 | 60 | 0.4461 | 0.1528 |
| 3 | 400 | 0.8348 | 1.130 | 70 | 0.4332 | 0.1282 |
| 3 | 500 | 0.7848 | 0.966 | 80 | 0.4199 | 0.1032 |
| 6 | 200 | 0.9816 | 1.742 | 50 | 0.4733 | 0.2056 |
| 6 | 300 | 0.9090 | 1.411 | 60 | 0.4639 | 0.1872 |
| 6 | 400 | 0.8672 | 1.246 | 70 | 0.4461 | 0.1528 |
| 6 | 500 | 0.7938 | 0.994 | 80 | 0.4367 | 0.1349 |
| 9 | 200 | 0.9370 | 1.531 | 50 | 0.4831 | 0.2251 |
| 9 | 300 | 0.8714 | 1.262 | 60 | 0.4726 | 0.2043 |
| 9 | 400 | 0.8270 | 1.103 | 70 | 0.4536 | 0.1673 |
| 9 | 500 | 0.7830 | 0.960 | 80 | 0.4464 | 0.1534 |

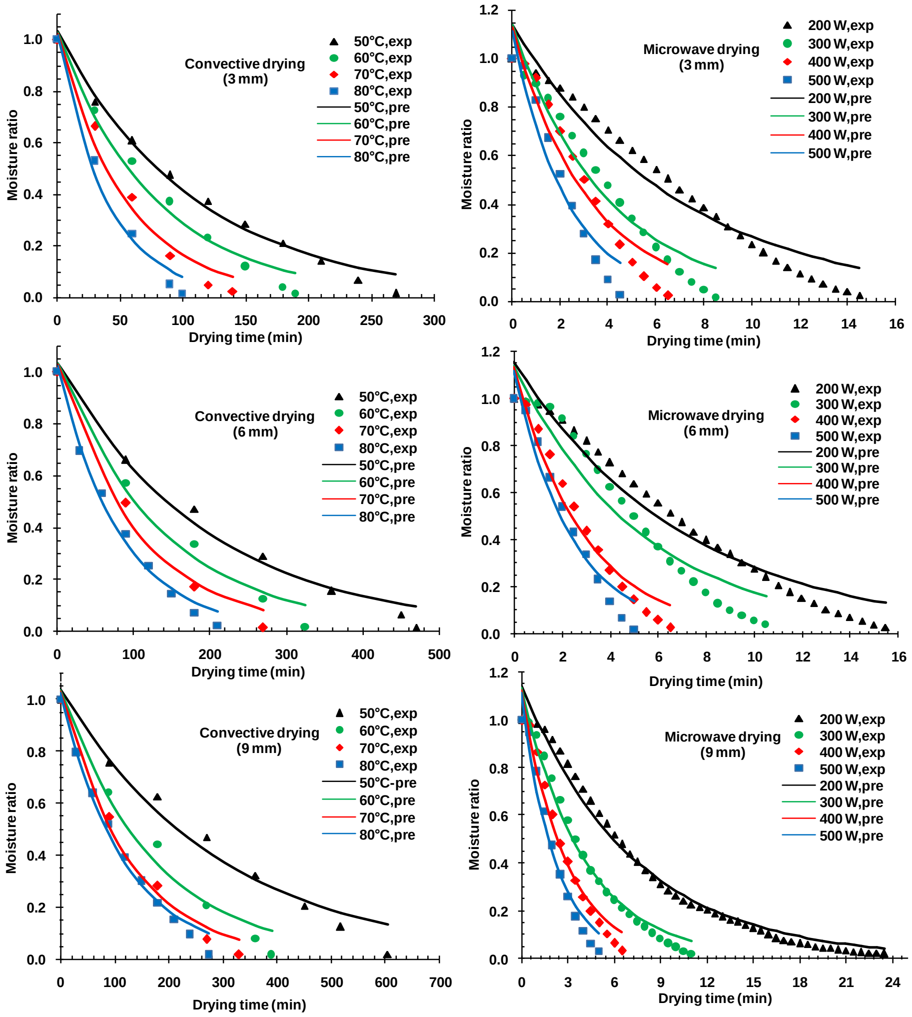


**Figure 4.** Experimental and predicted average dimensionless moisture ratio for different drying conditions of kiwi slice.





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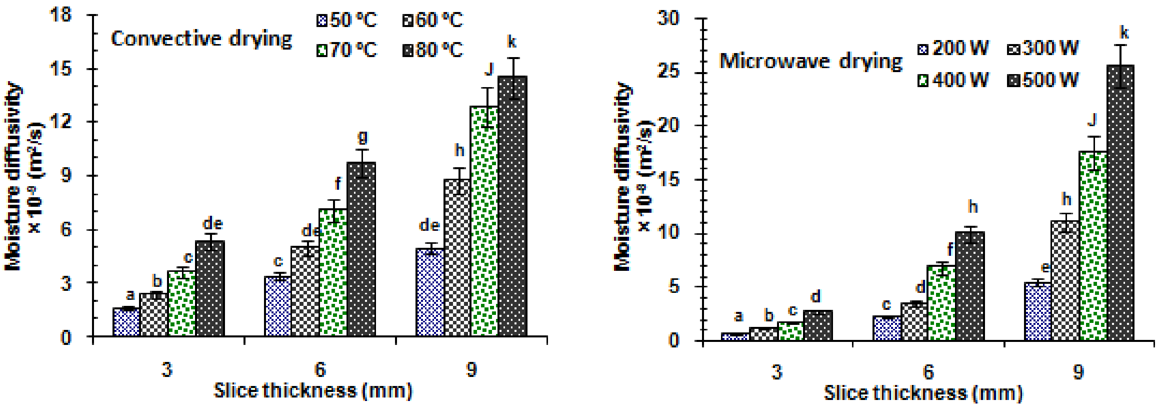


**Figure 5.** Moisture diffusivity of kiwi slices as a function of the drying conditions.

under different drying conditions. These values fell within the normally expected range of $D_m$ ($10^{-11}$ to $10^{-8}$ $m^2$ $s^{-1}$) for food materials (Beigi, 2015; Sharifian *et al.*, 2015).

As expected, the $D_m$ values of kiwi slices increased with the increase in slice thickness (8.04- to10.50-fold for microwave drying; 2.07- to 3.65-fold for convective drying) due to the effect of the surface hardening of the product ($p \leq 0.05$). Nguyen and Price (2007) found that the occurrence of surface hardening of thin slabs was faster than thick slabs, because the moisture evaporation rate of thin slabs was higher. A rapid surface hardening of thin slabs then hinders the moisture transfer during the drying process, leading to the $D_m$ value of thin slabs to be lower than that of thick slabs (Darvishi *et al.*, 2015). It can be seen from the abovementioned results that moisture diffusivity of the kiwi slice under microwave heating was higher (4.11-17.67-fold) than conventional drying. This result is attributed to the fact that drying by microwave power leads to higher temperatures and a larger driving force for heat transfer compared to those of convective drying. In other words, in microwave drying, due to the directly transmitted and absorbed energy by the water molecules, the volumetric heat generation in the wet sample results in higher interior temperatures and increase the activity of water molecules. Thus, the boiling point of water is reached substantially faster than would be possible in convective drying (Darvishi *et al.*, 2013; Wang *et al.*, 2007). The moisture diffusivity was estimated for drying condition as follows:

$$D_{m,mic} = 3.44\times10^{-14} P^{1.70} \exp\left(1.76\ L^{0.5}\right)$$
$$R^2 = 0.998 \tag{26}$$

$$D_{m,con} = 3.11\times10^{-9} P^{1.70} \exp\left(0.881\ L^{0.5} - \frac{747.4}{T^{1.5}}\right)$$
$$R^2 = 0.990 \tag{27}$$

The resulting values of $D_m$ are comparable to the mentioned 0.589-6.574 × $10^{-10}$ $m^2$ $s^{-1}$ values for convective drying of kiwi slice at 35-65°C, 0.3-0.9 m $s^{-1}$, and 7 mm slice thickness (Kaya *et al.*, 2010); 1.47-39.29×$10^{-9}$ $m^2$ $s^{-1}$ for microwave drying of kiwi slice at 200-500W and 3-9 mm (Darvishi *et al.*, 2016); 2.90-5.10×$10^{-10}$ $m^2$ $s^{-1}$ for convective drying of kiwi slice at 50-80°C, 0.5-2.0 m $s^{-1}$, and 4-6 mm (Darıcı and Sen, 2015); 1.74-2.24×$10^{-10}$ $m^2$ $s^{-1}$ for hot air drying of kiwi slices at 50-60°C and 8 mm (Doymaz, 2008); and 3.0-17.2×$10^{-10}$ $m^2$ $s^{-1}$ for convective drying of kiwi slices at 30-90°C and 6 mm (Simal *et al.*, 2005). The values obtained in this study are higher than those found by other researchers for microwave or convective dryings of the kiwi slice. The reason for such a difference might be the calculation of the moisture diffusion





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coefficient. Considering the objectives of the present work, we used the analytical model proposed by Dincer and Dost for the calculation of moisture diffusivity, while the listed researchers calculated the moisture diffusivity based on the Crank's solution of Fick's theoretical diffusion law.

### Mass Transfer Coefficient

Influence of drying conditions on mass transfer coefficient is shown in Figure 6. As can be seen, slices thickness, microwave power, and air temperature had a significant effect on $h_m$ ($p \leq 0.05$). The values of $h_m$ obtained from the microwave drying data and the convective drying of kiwi slices were 5.64-6.20×$10^{-5}$ and 1.93-4.95×$10^{-7}$ m $s^{-1}$, respectively. The $h_m$ increases with increasing the microwave power, drying air temperature, and slice thickness of kiwi samples. When samples are dried at a higher temperature or microwave power, the increased heating energy would increase the activity of water molecules resulting in a higher mass transfer rate (Haghi and Amanifard, 2008; Bezerra *et al*., 2015). In addition, the relative humidity of the drying air at a higher temperature was less compared to that at a lower temperature; the difference in the partial vapor pressure between the kiwi slices and their surroundings was greater for the higher drying temperature environment (Darvishi *et al*., 2015). The literature review conducted in this research indicated that the increase in $h_m$ with slice thickness is due to the effect of the exposed surface hardening resulting in the increased diffusion path of moisture out of the sample slices during the drying process (Darvishi *et al*., 2015; Nguyen and Price, 2007). Variation of the $h_m$ versus drying conditions are presented as follows:

$$\mathrm{h}_{\mathrm{m,mic}} = 2.98\times10^{-9} P^{1.15} \exp\left(0.9\, L^{0.5}\right) \quad (28)$$

$$R^2 = 0.992$$

$$\mathrm{h}_{\mathrm{m,mic}} = 4.47\times10^{-7} \exp\left(0.0625\, L - \frac{2634.4}{T^2}\right)$$

$$R^2 = 0.973 \quad (29)$$

These results were found in the range of those available in the existing literature for drying of various foods such as 0.727-2.21×$10^{-7}$ m $s^{-1}$ for hot air drying of potato slices (Akpinar and Dincer, 2005), 2.13-8.53×$10^{-6}$ m $s^{-1}$ for microwave drying of potato slices (Haghi and Amanifard, 2008), 1.46-3.39×$10^{-7}$ m $s^{-1}$ for hot air drying of apple slices (Beigi, 2015), 4.53-8.70×$10^{-7}$ m $s^{-1}$ for convective drying of passion fruit peel (Bezerra *et al*., 2015), and 0.50-42.50×$10^{-6}$ m $s^{-1}$ for convective drying of pumpkin slice (Raquel *et al*., 2012).

### Drying Time

The effect of drying conditions on the drying time is shown in Figure 7. As

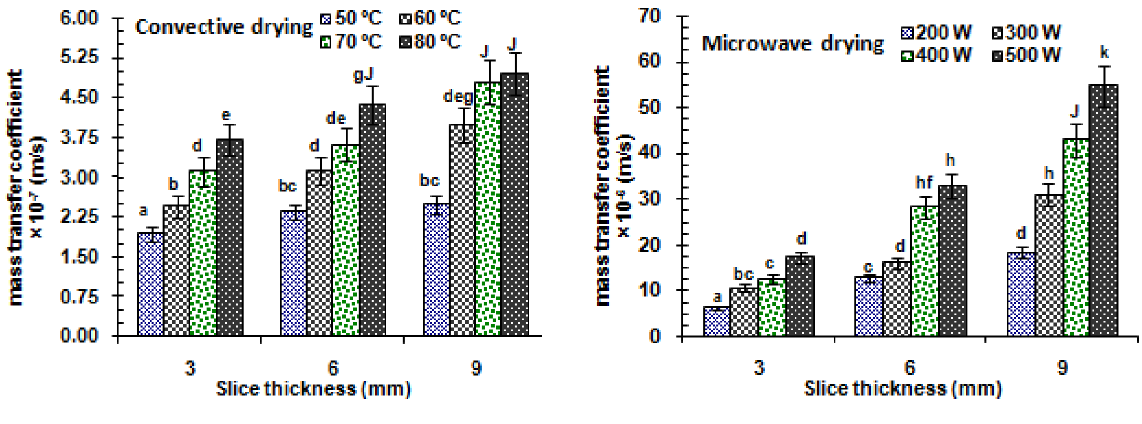


**Figure 6.** Comparison of mass transfer coefficient of kiwi slice in two different drying methods.

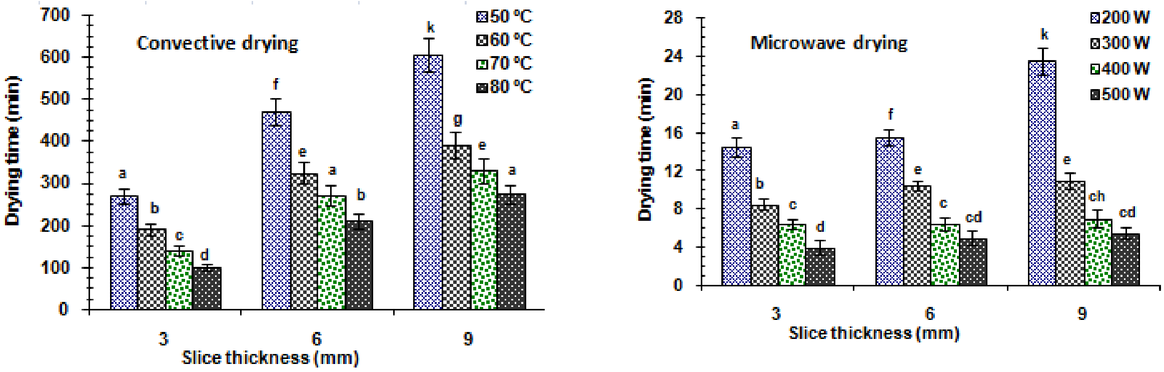


**Figure 7.** Effect of drying conditions on drying time.

expected, the increase in the drying air temperature or microwave power and the decrease in the slice thickness resulted in a decrease in the drying time ($p \leq 0.05$). These results are consistent with those obtained by Azizi *et al*. (2017) and Jafari *et al*. (2016) for reflectance window drying of the kiwi slice. The drying times required to remove 90% of the moisture content of kiwi samples in convective dryer varied from 90 (3 mm, 80°C) to 604 minutes (9 mm, 50°C). Corresponding values for microwave drying of kiwi slices were between 4 (3 mm, 500W) and 23.5 minutes (9 mm, 200W). As can be seen from Figure 7, the microwave drying time is 18- to 49-fold lower than the convective drying time of kiwi slices. This difference is because drying by microwave power leads to higher temperatures and, as a result, a larger driving force for heat transfer, as compared with those of convective drying. In other words, in microwave drying, the volumetric heat generation in the wet sample due to the directly transmitted and absorbed energy by the water molecules, a higher interior temperature and an increase in the activity of water molecules is reached. Thus, a quick reaching of the boiling point of water would be possible in convective drying.

In comparison with the slice thickness of 3 mm, the thickness of 9 mm caused a significant increase in drying time by about 71-200% for convective drying and 7.8-69% for microwave drying ($p < 0.05$). Such an increase is due to the reduced distance of the moisture travel and the increased surface area exposed to a given volume of the samples (Azizi *et al*., 2017; Darvishi *et al*., 2015). For both methods, the decrease in drying time (minute) is expressed by:

$$t_{con} = 227.4 \exp\left(-\frac{3.46}{L} + \frac{3338}{T^2}\right)$$

$$R^2 = 0.981 \quad (30)$$

$$t_{mic} = \frac{10^3}{20.52 - 0.0381L^3 - 0.0177P^{1.5}}$$

$$R^2 = 0.992 \quad (31)$$

## Activation Energy

The results of the fitting procedure of Equations (17-20) on values of moisture diffusivity and mass transfer coefficient for the calculation of the activation energy are shown in Figure 8 and Table 6. This energy was found to be 27.98-38.57 kJ $mol^{-1}$ for convective moisture diffusion and 17.23-20.44 kJ $mol^{-1}$ for convective mass transfer model. In comparison, for microwave drying, they were 21.30-24.64 W $g^{-1}$ for moisture diffusion and 13.95-15.65 W $g^{-1}$ for mass transfer model. As can be seen, values of activation energy for convective mass transfer model were much lower than moisture diffusion. The lower activation

**Table 6.** Values of activation energy and pre-exponential factor of Arrhenius Equation.

| Drying method | $L$ (mm) | $D_0$ ($m^2$ $s^{-1}$) | $E_{ad}$ | $h_0$ (m $s^{-1}$) | $E_{am}$ |
|---|---|---|---|---|---|
| Convective | 3 | $27.37\times10^{-4}$ | 38.57 | $3.95\times10^{-4}$ | 20.44 |
| | 6 | $6.68\times10^{-4}$ | 32.69 | $2.42\times10^{-4}$ | 18.53 |
| | 9 | $2.12\times10^{-4}$ | 27.98 | $1.87\times10^{-4}$ | 17.23 |
| Microwave | 3 | $5.48\times10^{-7}$ | 20.13 | $3.03\times10^{-5}$ | 14.86 |
| | 6 | $21.69\times10^{-7}$ | 22.18 | $5.94\times10^{-5}$ | 15.17 |
| | 9 | $65.02\times10^{-7}$ | 23.63 | $10.72\times10^{-5}$ | 18.71 |

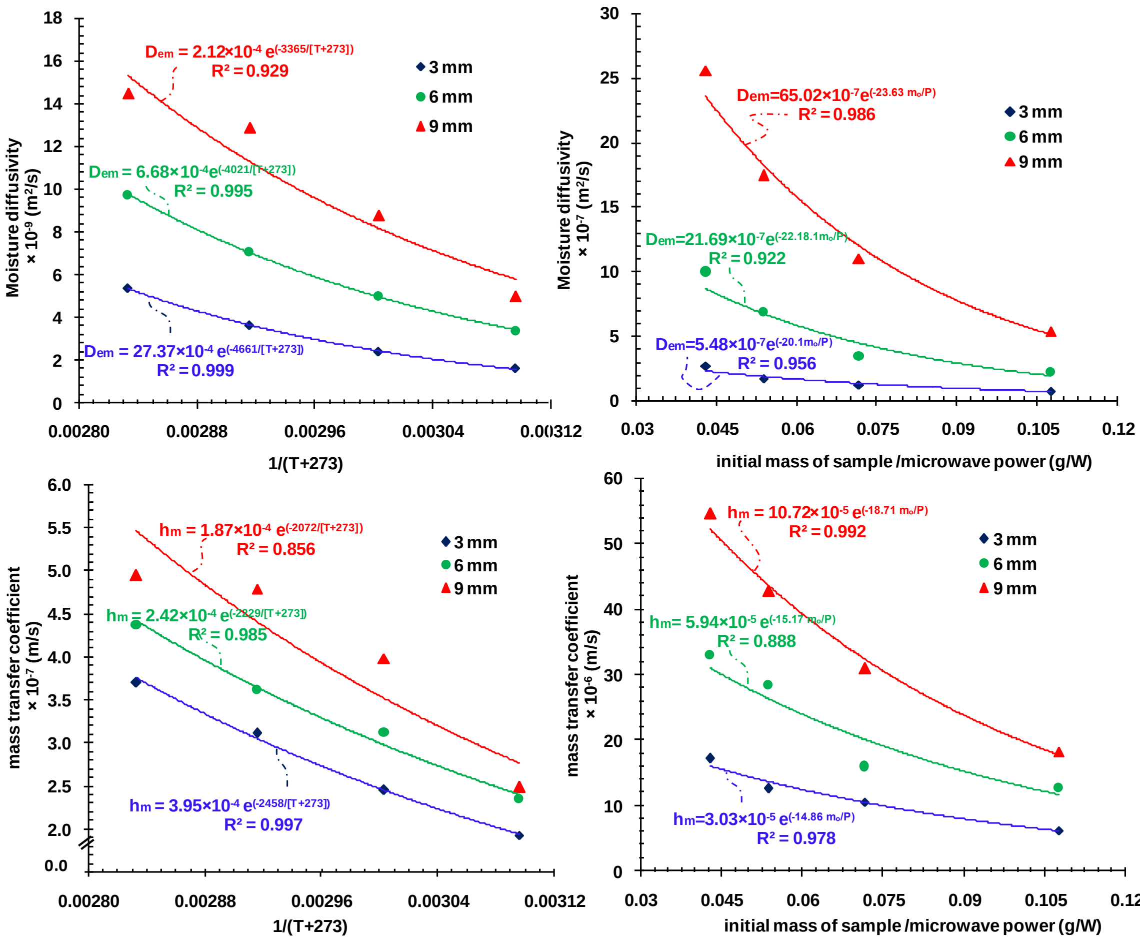


**Figure 8.** The Arrhenius relationships between the variables and mass transfer characteristics.

energy means higher moisture diffusivity or mass transfer coefficient in the drying process (Sharma and Prasad, 2004; Darvishi *et al.*, 2015). These values are similar to those proposed in the literature by several authors for kiwi slices; e.g., 27.71-29.12 kJ mol$^{-1}$ (Kaya *et al.*, 2008), 34.33–38.07 kJ mol$^{-1}$ (Darıcı and Sen, 2015), and 17.96-21.38 W g$^{-1}$ (Darvishi *et al.*, 2016). Also, Table 6 presents that the activation energy for convective moisture diffusion decreases with increase in slice thickness, while it increases with increase in slices thickness for microwave drying. An increase in moisture diffusion (with slice thickness) implies that lower energy is required to




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break the bond between the water molecules of kiwi samples. In other words, activation energy decreases with increase in the moisture diffusion or mass transfer coefficient values. In general, high activation energy values are associated with materials in which water is more strongly bound to the material structure and, consequently, water removal is done by the sample's structure (Bezerra *et al*., 2015).

## CONCLUSIONS

The mass transfer parameters of the kiwi slice (namely, moisture diffusivity, mass transfer coefficient, Biot number, activation energy, drying time, and drying rate) were evaluated using the Dincer and Dost model during convective and microwave drying. Moisture diffusivity and mass transfer coefficient were found to increase with an increase in sample thickness, drying temperature, and microwave power. The results showed a reasonably good agreement between the values predicted from the correlation and the experimental observations. The microwave drying gives a shorter drying time (4-23.5 minutes) because of the higher mass transfer coefficients compared with the convective drying (90-604 minutes). Values of Bi obtained for all combinations for drying conditions were 0.103-0.225 for CD and 0.960-1.742 for MD. The results also showed that the energy required to trigger the mass transfer process was lower (1.6- to1.9-fold for CD and 1.3- to 1.5-fold for MD) than the activation energy of moisture diffusion.

## Nomenclature

$A_1$, $B_1$ Constants of Equation (3)
Bi Biot number (-)
CD Convective Drying
MD Microwave Drying
$D_0$ Pre-exponential factor of Arrhenius Equation ($m^2\ s^{-1}$)
$D_m$ Moisture Diffusivity ($m^2\ s^{-1}$)
$E_{ad}$ Activation Energy of diffusion model (W $g^{-1}$ for MD; KJ $mol^{-1}$ for CD)
$E_{ad}$ Activation Energy of mass transfer model (W $g^{-1}$ for MD; KJ $mol^{-1}$ for CD)
$F_o$ Fourier number (-)
G Log factor of the Henderson and Pabis Model (-)
$h_0$ Pre-exponential factor of Arrhenius Equation (m $s^{-1}$)
$h_m$ Mass transfer coefficient (m $s^{-1}$)
L Thickness of slices (mm)
M Moisture content (kg water $kg^{-1}$ dry matter)
$m_0$ Initial mass (g)
$M_0$ Initial Moisture content (kg water $kg^{-1}$ dry matter)
$M_e$ Equilibrium Moisture content (kg water $kg^{-1}$ dry matter)
MR Moisture Ratio (-)
$MR_{exp}$ Experimental Moisture Ratio (-)
$MR_{pre}$ Predicted Moisture Ratio (-)
$M_t$ Moisture content at any time (kg water $kg^{-1}$ dry matter)
n Constant, positive integer
N Number of observations (-)
P Microwave Power (W)
R Universal gas constant (8.314 J $mol^{-1}$ K)
$R^2$ Coefficient of determination
RMSE Root Mean Square Error (-)
S Drying rate constant (1/s)
T Drying air Temperature (ºC)
t Time (s)
W Uncertainty
y Independent variable
z Number of coefficients and constants of the model (-)
$\mu_1$ Root of the characteristic equation
$\chi^2$ Reduced Chi-square (-)

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# تاثیر شرایط مختلف خشک کردن بر پارامترهای انتقال جرم در ورقه های کیوی

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## چکیده

در این مطالعه، تاثیر شرایط مختلف خشک کردن بر ویژگی‌های انتقال جرم ورقه های کیوی با استفاده از مدل تحلیلی ارائه شده توسط دینسر و داست مورد ارزیابی قرار گرفت. آزمایشات خشک کردن با هوای گرم در محدوده دمایی ۵۰ – ۸۰ درجه سانتیگراد با سرعت هوای ۰/۵ متر ثانیه و مایکروویو در محدوده توانی 200 – 500وات به صورت لایه نازک با ضخامت ۳، ۶ و ۹ میلیمتر انجام گرفت .نتایج نشان دهنده آن است که ویژگی‌های انتقال جرم به شدت وابسته به شرایط خشک کردن است. پارامترهای نفوذ رطوبت، ضریب انتقال جرم، عدد بایوت و زمان خشک شدن برای روش خشک کردن هوای گرم به ترتیب در محدوده ۰/۱۶– ۸–۱۰× ۱/۴۵ متر مربع بر ثانیه، ۱/۹۳– ۷–۱۰× ۴/۹۵ متر بر ثانیه، ۰/۱۰۳ – ۰/۲۲۵ و ۹۰–۶۰۴ دقیقه متغیر است. در مقایسه، برای خشک کردن مایکروویو این مقادیر به ترتیب در محدوده ۰/۶۶– ۸–۱۰× ۲۵/۶۰ متر مربع بر ثانیه، ۰/۶۲– ۵–۱۰× ۵/۶۴ متر بر ثانیه، ۰/۹۶۰ – ۱/۷۴۲ و 5/23-4دقیقه قرار گرفته اند. نتایج نشان داد که انرژی فعال‌سازی برای انتشار رطوبت بیشتر از انرژی لازم برای انتقال جرم انتقال جرم از سطح است.





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