



## Experimental and Modeling Investigation of Mass Transfer during Infrared Drying of Kumquat Slices

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### Abstract

In this work, mass transfer of kumquat slices was investigated during infrared drying. The effect of the infrared radiation power (50-88 W) on the drying characteristics of the kumquat slices was evaluated as the drying parameter. It was determined that the infrared power affected the drying and colour characteristics of kumquat slices and drying time decreased with increased infrared power. Five different mathematical models were evaluated for moisture ratios using nonlinear regression analysis. The results of regression analysis indicated that the Midilli & Kucuk model is the best model to describe the drying behaviour with the lowest  $\chi^2$  and RMSE values and highest  $R^2$  values. The effective moisture diffusivity at each infrared power was determined by Fick's second law of diffusion, an increase in the power led to increase in the effective moisture diffusivity between  $8.31 \times 10^{-9}$  and  $1.89 \times 10^{-8}$  m<sup>2</sup>/s. The dependence of effective moisture diffusivity on infrared power was expressed by a modified Arrhenius type equation. Activation energy was estimated by a modified Arrhenius type equation as 1.92 kW/kg. A positive effect was observed on the  $\Delta E$  with increasing in infrared power and with rising in infrared radiation power it was

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decreased. Whereas, it was observed that the chroma values increased with rising in infrared radiation power.

*Keywords:* Activation energy, Effective moisture diffusivity, Kumquat, Infrared drying.

## **Kızılötesi Kurutma Sırasında Kumquat Dilimlerinin Kütle Transferinin Deneysel ve Modelleme İncelemesi**

### **Özet**

Bu çalışmada, kızılötesi kurutma sırasında kumquat dilimlerinin kütle transferi araştırılmıştır. Kurutma parametresi olarak kızılötesi radyasyon gücünün (50-88 W) kumquat dilimlerinin kurutma karakteristiği üzerindeki etkisi değerlendirilmiştir. Kızılötesi gücün, kumquat dilimlerinin kurummasını ve renk özelliklerini etkilediği ve kuruma süresinin artan kızılötesi güç ile azaldığı belirlenmiştir. Doğrusal olmayan regresyon analizi kullanılarak beş farklı matematiksel model nem oranları için değerlendirilmiştir. Regresyon analiz sonuçları Midilli & Kucuk modelinin en düşük  $\chi^2$  ve RMSE değerleri ve en yüksek  $R^2$  değerleri ile kurutma davranışını tanımlayan en iyi model olduğunu göstermiştir. Her bir kızılötesi güçteki efektif nem difüzyonu, Fick'in ikinci difüzyon yasası ile belirlenmiştir, güçteki artış efektif nem difüzyonunda  $8.31 \times 10^{-9}$  ve  $1.89 \times 10^{-8}$  m<sup>2</sup>/s arasında artışa yol açmıştır. Efektif nem difüzyonun kızılötesi güce bağımlılığı modifiye bir Arrhenius tipi denklem ile ifade edilmiştir. Aktivasyon enerjisi modifiye Arrhenius tipi denklem ile 1.92 kW/kg olarak hesaplanmıştır. Kızılötesi güçteki artma ile  $\Delta E$ 'de pozitif bir etki gözlemlenmiş ve kızılötesi radyasyon gücündeki yükselme ile bu etki azalmıştır. Bununla birlikte kızılötesi radyasyon gücündeki yükselmenin chroma değerlerini artırdığı gözlenmiştir.

*Anahtar Kelimeler:* Aktivasyon enerjisi, Efektif nem difüzyonu, Kumquat, Kızılötesi kurutma.

## 1. Introduction

Kumquats which is the smallest of the citrus fruits, are an excellent source of nutrients and phytochemicals including flavonoids, vitamins, carotenoids, and terpenoids, with a marked antioxidant activity [1]. As in the other citrus species, in kumquat essential oils are greatly accumulated in the oil glands of the peel. Owing to their health benefits, they are traditionally used as folk medicine in Asian countries. However, rather than being important as a source of raw material for applications in pharmaceutical, sanitary, cosmetic, agricultural and food industries, kumquats play a very important role for the flavor and taste conferred the fruit as well as for their healthy properties, as they are consumed as a whole, including their peel. Kumquats that is native to south-eastern China spread, not just in Asia and in Japan but also in Argentina, Brazil, USA, in the Mediterranean region [2].

The postharvest shelf life of kumquat fruit is relatively short due to the effect of *Penicillium*, which result in high levels of decay. Also, unlike other citrus fruits, its thin, edible peels don't protect them as well as the thicker peels of oranges or lemon and kumquats don't have a long shelf life. Therefore, kumquat must be subjected to some form of preservation such as liqueurs, marmalades, sauces and it can be candied or preserved whole in sugar syrup. Drying can make the product available throughout the year at reasonable cost. Dried whole kumquats are often used to cure inflammatory syndromes of respiratory tract, such as coughing, hoarseness and sore throats [2-3].

Drying is a traditional or industrial preservation method that is used in the food industry. The drying process is intended to remove water from foodstuff to prevent microbial spoilage and chemical alterations, thus prolonging shelf-life while realizing space and weight savings. This process generally involves removal of water by application of heat. Improper drying may lead to irreversible damages to product quality, high energy and time consumption, unseasonable charges, etc. [4]. Drying of agricultural products can be performed using different methods, including traditional and industrial drying. Infrared drying has gained popularity as an alternative drying method for obtaining high quality dried fruits, vegetables and grains [5].

Infrared drying has gained popularity as an alternative drying method for agricultural products. When infrared radiation is used to warm up or dry moist materials, it penetrates into them and the energy of radiation converts into heat [5]. Compared with hot air drying, infrared radiation heating offers many advantages such as greater energy efficiency, heat transfer rate, and heat flux, which results in reduced drying time and higher drying rate. Some of agricultural products have been successfully dried by the infrared application and/or by a combined infrared-assisted convection process and others [6-8]. However, the infrared drying process of kumquat has not been reported in literature. The main objectives of this study were to investigate the effect of infrared power on drying and color characteristics, fit the experimental data to five thin-layer drying models, and compute effective moisture diffusivity and activation energy of kumquat slices. Please write subtitles and their contents of your manuscript here.

## **2. Material and Methods**

Kumquat samples were obtained from a local market in Antalya. They were packed into plastic bags and stored in a refrigerator at 4°C prior to use. The initial moisture content of kumquats was determined by using an oven at 105°C for 24 h. Triplicate samples were used for the determination of moisture content and the average values were reported as 81.50 %, w.b. (4.405 kg water/kg dry matter, d.b.).

Drying experiments were carried out in a moisture analyzer (Snijders Moisture Balance). The experiments were carried out using several infrared power levels such as 50, 62, 74 and 88 W. Before the drying process, the samples were separated evenly and spread homogeneously over the pan. The power level was set from the control unit of the equipment. Approximately 50 g of sample, the half thickness (L) of a layer was about 13.25 mm, was put into the dryer after weighing. Moisture loss was recorded at 30 min intervals during drying. A digital balance (Mettler-Toledo AG) with 0.1 g accuracy was employed in recording the sample weight. Drying was continued until the sample weight attained a constant value. The drying process was continued until the moisture content remaining in the sample was about 0.425±0.02 kg water/kg dry matter (d.b.). The dried products were cooled, packaged in low-density polyethylene bags and

stored in incubators at ambient temperature. The experiments were run in triplicate and the drying curves were plotted using the average values of the moisture content.

## 2.1 Mathematical Modelling

Five semi-theoretical models were selected to describe the drying kinetics of the samples (Table 1).

**Table 1.** Mathematical models applied to the drying curves

Model name	Model	Reference
Lewis	$MR = \exp(-kt)$	El-Beltagy et al. [9]
Henderson & Pabis	$MR = a \exp(-kt)$	Erbay and Icier [10]
Logarithmic	$MR = a \exp(-kt) + c$	Afolabi et al. [11]
Page	$MR = \exp(-kt^n)$	Falade and Ogunwolu [12]
Midilli & Kucuk	$MR = a \exp(-kt^n) + bt$	Midilli and Kucuk [13]

*a, b, c, k and n* empirical constants and coefficients in the drying models

The moisture content (M), moisture ratio (MR) and drying rate (DR) of kumquats were calculated using the following equations:

$$M = \frac{W - W_1}{W_1} \quad (2.1)$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2.2)$$

$$DR = \frac{M_t - M_{t+dt}}{dt} \quad (2.3)$$

where M is the moisture content (kg water/kg dry matter), W is the weight of sample (kg),  $W_1$  is the dry matter content of sample (kg), and t is the drying time (min).  $M_0$ ,  $M_e$ ,  $M_t$  and  $M_{t+dt}$  are the initial moisture content, the equilibrium moisture content, the

moisture content at  $t$  and  $t+dt$  (kg water/kg dry matter), respectively. As the  $M_e$  is very small compared to  $M_0$  and  $M_t$  values, the  $M_e$  can be neglected and  $MR$  can be expressed as  $M_t/M_0$  [7].

## 2.2 Data Analysis

Experimental data were analyzed using the Statistica 8.0.550 (StatSoft Inc., USA) software package. The parameters of the models were estimated using a non-linear regression procedure based on the Levenberg-Marquardt algorithm. The fitting quality of the experimental data to all models was evaluated using the coefficient of determination ( $R^2$ ), reduced chi-square ( $\chi^2$ ) and root mean square error (RMSE). The  $R^2$ ,  $\chi^2$  and RMSE were calculated from the following formulas:

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^N (\overline{MR}_{pre} - MR_{exp,i})^2} \quad (2.4)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (2.5)$$

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]^{1/2} \quad (2.6)$$

where  $MR_{exp,i}$  and  $MR_{pre,i}$  are the experimental and predicted dimensionless moisture ratios, respectively;  $N$  is the number of observations;  $z$  is the number of constants. A higher  $R^2$  value and lower  $\chi^2$  and RMSE values indicate a better fit [14].

## 2.3 Calculation of Effective Moisture Diffusivity

Fick's second law of diffusion equation was used to fit the experimental drying data for the determination of effective moisture diffusivity coefficients.

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2 M}{\partial x^2} \quad (2.7)$$

where  $M$  is the moisture content (kg water/kg dry matter),  $t$  is the drying time (s), and  $D_{eff}$  is the effective moisture diffusivity ( $m^2/s$ ). The solution of diffusion Eq. (2.7) for slab geometry is solved by Crank [15] and supposed uniform initial moisture distribution, negligible external resistance, constant temperature and diffusivity, and negligible shrinkage:

$$MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2}\right) \quad (2.8)$$

where  $D_{eff}$  is the effective moisture diffusivity ( $m^2/s$ ),  $L$  is the half thickness of the slab (m), and  $n$  is the positive integer. Eq. (2.8) can be further simplified to only the first term of the series and expressed in a logarithmic form for long drying periods:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{4L^2}\right) \quad (2.9)$$

The effective moisture diffusivity was calculated from the slope ( $K$ ) of a straight line, plotting experimental drying data in terms of  $\ln(MR)$  versus time according to Eq. (2.9).

$$K = \frac{\pi^2 D_{eff}}{4L^2} \quad (2.10)$$

## 2.4 Estimation of Activation Energy

Temperature was not a directly measurable quantity during the infrared power drying process used in this study. For the calculation of activation energy, modified form of Arrhenius equation shows the relationship between the effective moisture diffusivity and the infrared power to sample weight [16].

$$D_{eff} = D_0 \exp\left(-\frac{E_a m}{p}\right) \quad (2.11)$$

where  $D_0$  is the pre-exponential factor of Arrhenius equation ( $m^2/s$ ),  $E_a$  is the activation energy (W/kg),  $p$  is the infrared output power (W), and  $m$  is the mass of the product (kg).

## 2.5 Colour

The colour values of the fresh and dried samples, at between 50 and 88 W powers, were evaluated using a hand-held tristimulus colorimeter (Chroma Meter-CR-400). The colour brightness coordinate L measures the whiteness value of a colour and ranges from black at 0 to white at 100. The chromaticity coordinate a measures red when positive and green when negative, and the chromaticity coordinate b measures yellow when positive and blue when negative. For the colour determinations, five measurements were done, and the corresponding average and standard deviation were calculated for each set of kumquat slices, fresh and dried at each infrared power. The Chroma and total color differences ( $\Delta E$ ) calculated using Equations. (2.12) and (2.13), respectively:

$$C = \sqrt{a^2 + b^2} \quad (2.12)$$

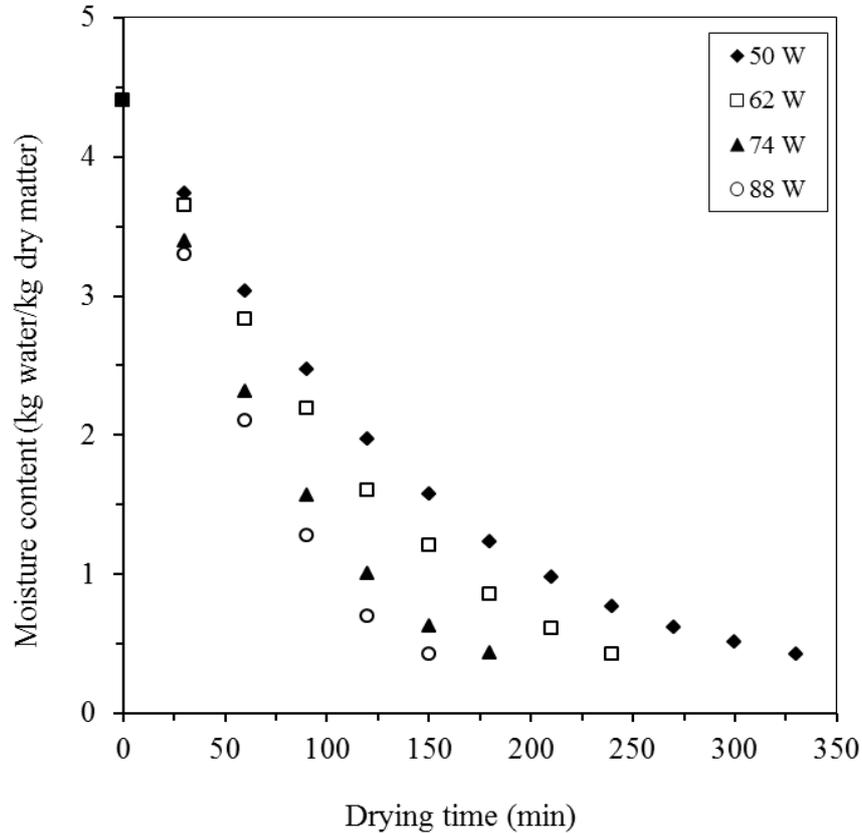
$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (2.13)$$

## 3. Results and Discussion

### 3.1 Analysis of Drying Curves

The effect of infrared power on moisture content and drying time is shown in Figure 1. The infrared power had a significant effect on the moisture content of the kumquat slices, as expected. It is observed that in infrared drying, an increase in the power level resulted in a decrease at drying time where the required time to reach the final moisture content at the power levels of 50, 62, 74 and 88 W, were about 330, 240, 180 and 150 min, respectively. The average drying rates increased 2.2 times as infrared power increased from 50 W to 88 W. In fact, at higher infrared powers, more heat is generated within the material leading to more vapour pressure differences between the

centre and surface of the product and consequently, increases the drying rate. This observation agree well with the results reported in the literature for infrared drying of different products such as lemon [17], red pepper [18], and spinach leaves [19].



**Figure 1.** Moisture content during drying time at different infrared powers

### 3.2 Drying Rate

The drying rate curves of kumquat slices are shown in Figure 2. It is clear that the drying rate decreases continuously with moisture content. The drying rates were higher in the beginning of the process, and then decreased with a decrease in moisture content of the samples. The reason for the decrease in drying rate might be due to a reduction in the porosity of samples caused by shrinkage with advancement, which increased the resistance to movement of water leading to further fall in drying rates [20]. This observation is in agreement with previous studies on infrared drying of foodstuffs [21,22]. In all cases constant drying rate period was not observed and therefore the

drying process occurred in the falling drying rate period. These results are in good agreement with those in earlier studies of various vegetables [17,19,23].

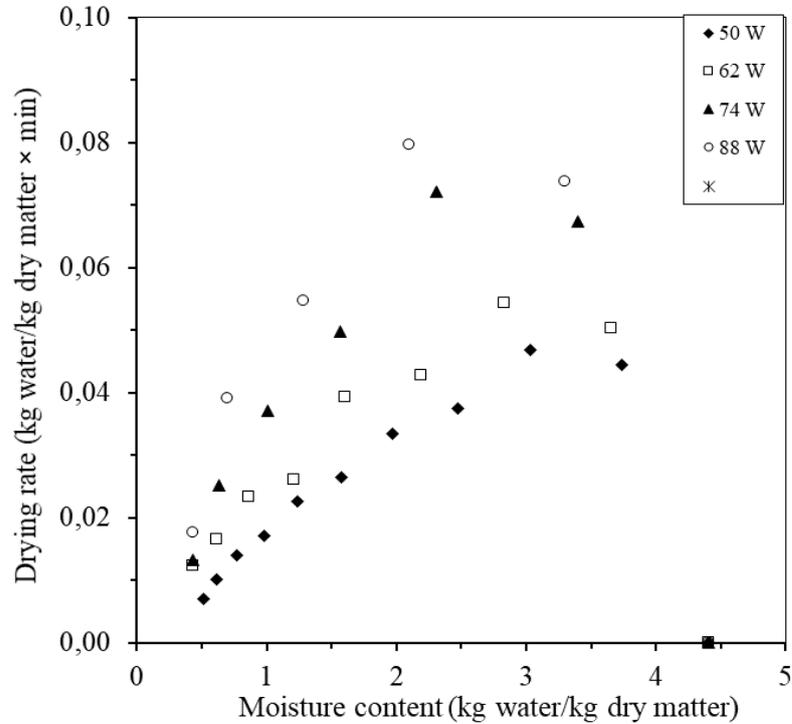
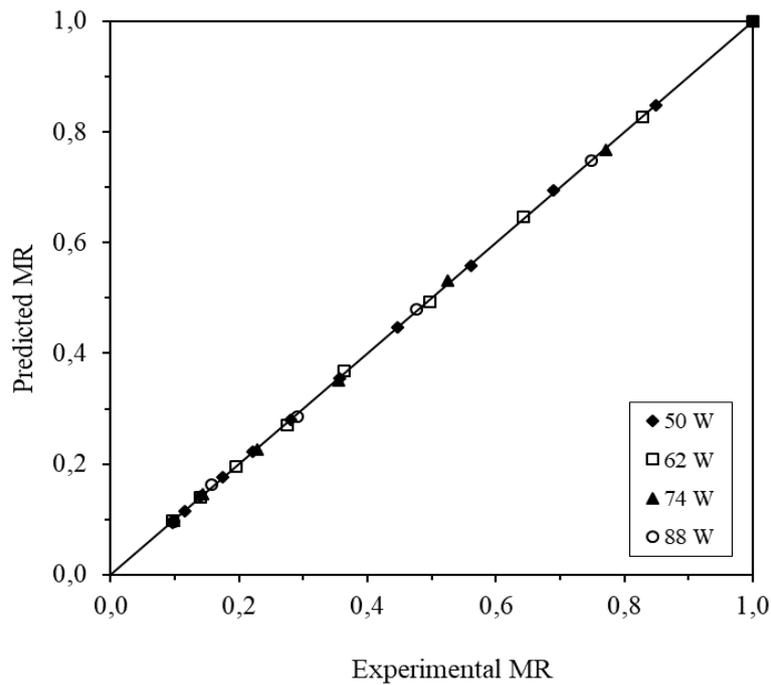


Figure 2. Drying rate as a function of moisture content at different infrared powers

### 3.3 Evaluation of Models

The moisture content data obtained from the drying experiments were fitted five thin-layer drying models identified in Table 1. The best model selected is based on the highest  $R^2$  and the lowest  $\chi^2$  and RMSE values. Results of the statistical computing are shown in Table 2. The  $R^2$  values for all models were above 0.98. Among the five thin-layer drying models tested, Midilli & Kucuk model obtained the highest  $R^2$  values and the lowest  $\chi^2$  and RMSE values in all the infrared drying conditions studied. It is clear that, the  $R^2$ ,  $\chi^2$  and RMSE values of this model were changed between 0.9998-0.9999, 0.000007-0.000038 and 0.006209-0.007845, respectively. Figure 3 compares experimental data with those predicted with the Midilli & Kucuk model for kumquat slices. As shown, the predicted moisture ratios are generally banded near to a 45° straight line, indicating the capability of the model to describe the drying behaviour of the samples appropriately.



**Figure 3.** Experimentally determined and predicted moisture ratios of kumquats

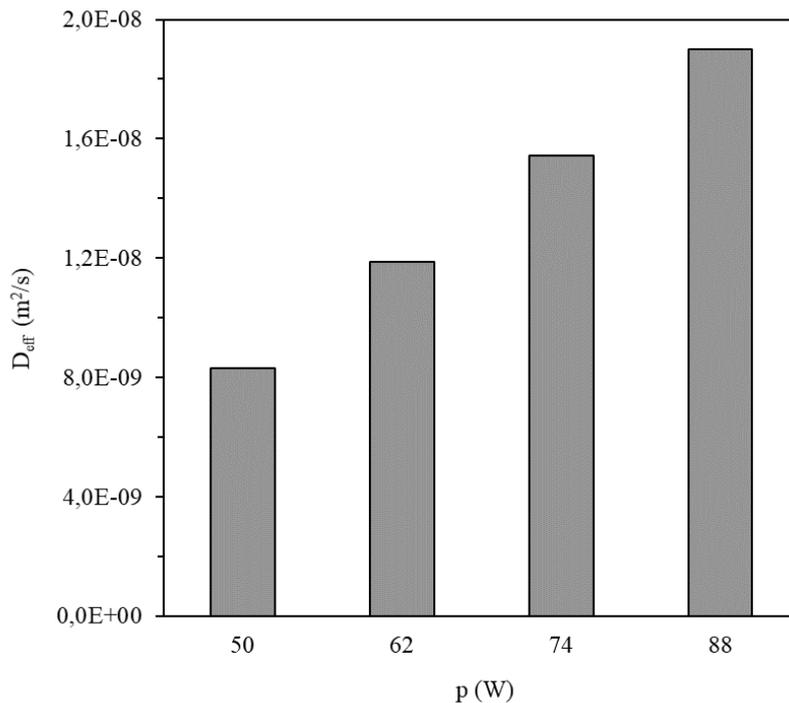
**Table 2.** Statistical parameters of models at different infrared powers

<i>Model name</i>	<i>p (W)</i>	<i>R</i> <sup>2</sup>	<i>χ</i> <sup>2</sup>	<i>RMSE</i>
Lewis	50	0.9963	0.000333	0.049828
	62	0.9900	0.001010	0.074413
	74	0.9897	0.001169	0.065288
	88	0.9834	0.002075	0.081637
Henderson & Pabis	50	0.9976	0.000234	0.041752
	62	0.9927	0.000842	0.068283
	74	0.9918	0.001115	0.065985
	88	0.9860	0.002184	0.084516
Logarithmic	50	0.9986	0.000148	0.032412
	62	0.9984	0.000204	0.029955
	74	0.9970	0.000507	0.038245
	88	0.9957	0.000892	0.046874
Page	50	0.9972	0.000027	0.012611
	62	0.9998	0.000015	0.007621
	74	0.9997	0.000036	0.009957
	88	0.9997	0.000040	0.010425
Midilli & Kucuk	<b>62</b>	<b>0.9999</b>	<b>0.000007</b>	<b>0.006209</b>
	<b>74</b>	<b>0.9999</b>	<b>0.000013</b>	<b>0.006840</b>
	<b>88</b>	<b>0.9998</b>	<b>0.000028</b>	<b>0.007845</b>
	<b>104</b>	<b>0.9998</b>	<b>0.000038</b>	<b>0.006930</b>

### 3.4 Effective Moisture Diffusivity and Activation Energy

By plotting  $\ln(MR)$  against drying time (Figure 4) and using the slope methods the effective moisture diffusivity of the samples was calculated under different drying conditions. The values of effective diffusivity ( $D_{eff}$ ) were calculated by using Eq. (3.2) and are shown in Figure 5. The  $D_{eff}$  values of kumquat slices in the infrared drying at 50-88 W varied between  $8.31 \times 10^{-9}$  and  $1.89 \times 10^{-8}$   $m^2/s$ . It can be seen that  $D_{eff}$  values increased greatly with increasing infrared power. Drying at 88 W has the highest value of  $D_{eff}$  and the lowest value was obtained for 50 W. The values of  $D_{eff}$  from this study lie within in general range  $10^{-12}$  to  $10^{-8}$   $m^2/s$  for drying of food materials [24]. The effect of infrared power on effective diffusivity is defined by the following equation:

$$D_{eff} = 2 \times 10^{-11} p - 9 \times 10^{-10} \quad (R^2 = 0.9851) \quad (3.1)$$



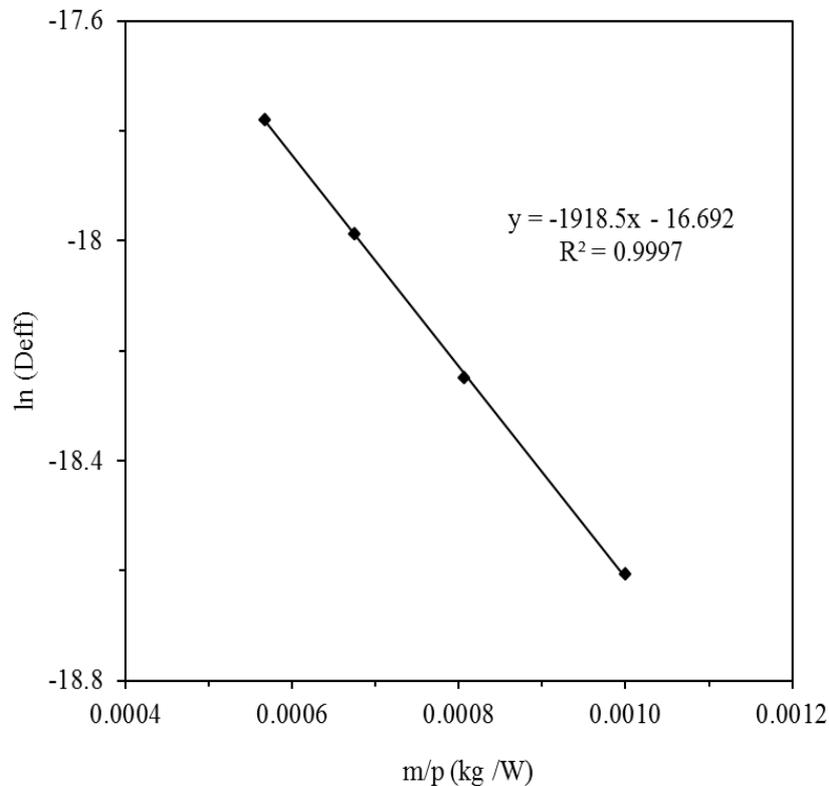
**Figure 4.** Variation of effective moisture diffusivity with infrared powers

The activation energy can be determined from the slope of Arrhenius plot,  $\ln(D_{eff})$  versus  $m/p$  (Eq. (3.2)). The  $\ln(D_{eff})$  as a function of the sample weight/infrared power was plotted in Figure 5. The slope of the line is  $(-E_a)$  and the intercept equals to  $\ln(D_0)$ . The results show a linear relationship due to Arrhenius type dependence. Eq.

(3.2) shows the effect of sample weight/infrared power on  $D_{\text{eff}}$  of samples with the following coefficients:

$$D_{\text{eff}} = 8.022 \times 10^{-9} \exp\left(-\frac{6746.1 \text{ m}}{p}\right) \quad (R^2 = 0.9775) \quad (3.2)$$

The estimated values of  $D_0$  and  $E_a$  from modified Arrhenius type exponential Eq. (2.11) are  $5.633 \times 10^{-8} \text{ m}^2/\text{s}$  and  $1.92 \text{ kW/kg}$ , respectively



**Figure 5.** Arrhenius-type relationship between effective moisture diffusivity and infrared powers

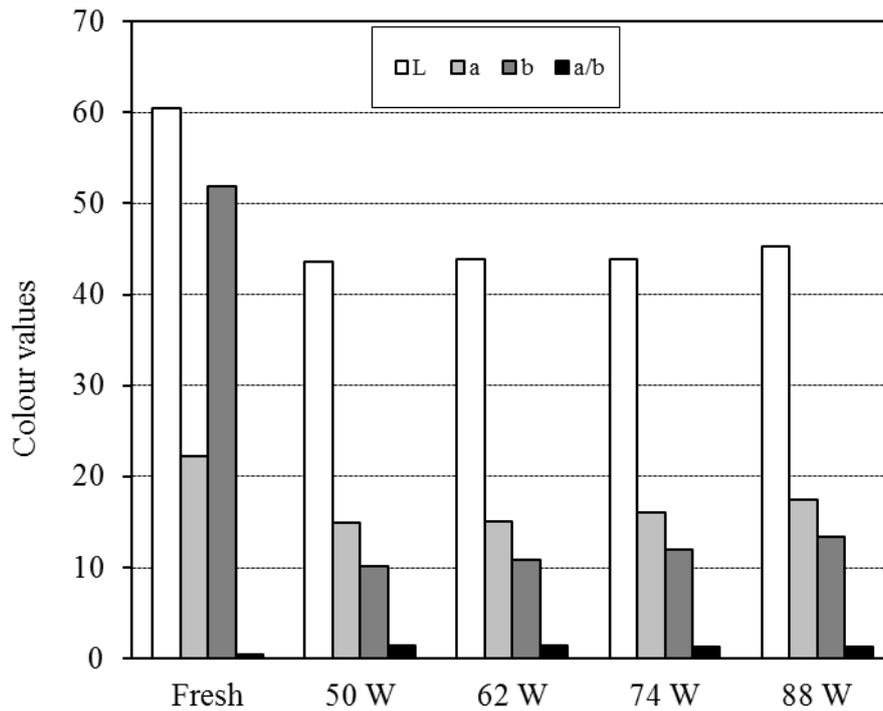
### 3.5 Colour Evaluation

Colour has to be considered as a special parameter that seems to be one of the most important criteria determining product quality and consumer preference. The average values for the colour parameters of fresh kumquat slices were as follows:  $L=60.49$ ,  $a=22.24$ , and  $b=51.88$ . The colour parameters of dried samples are presented in Figure 6. and Table 3. It can be seen that the entire dried kumquat slices had lower

values of L than the fresh samples. The L values which show lightness of product were ranged between 43.60 and 45.22. The lowest L value evaluated for dried product at 50 W. The decrease in L values might be caused by browning reactions [25]. It can be clearly seen from the Table 3, the values of an increased as the power output increased. Therefore, the samples tended toward greater redness values with the progressing drying time. On the other hand, the creation of brown pigments in the effect of non-enzymatic processes (Maillard reaction) during drying process might play an important role in the production of red colour [26]. The values of b were increased with increasing of power output, indicating dried samples were yellower at high power output (high temperature). The chroma is measure of chromaticity (C), which denotes the purity or saturation of the colour. The chroma (C) values showed an increase during process. Chroma (C) values varied from 18.08 to 21.93 at different infrared powers. Whereas, with increasing in infrared power from 50 to 88 W,  $\Delta E$  was decreased from 45.62 to 41.71, respectively.

**Table 3.** Results of colour values for kumquat slices

<b>p (W)</b>	<b>L</b>	<b>a</b>	<b>b</b>	<b>C</b>	<b><math>\Delta E</math></b>
50	43.60	14.99	10.12	18.08	45.62
62	43.88	15.11	10.88	18.62	44.80
74	43.92	16.08	12.00	20.06	43.62
88	45.22	17.40	13.36	21.93	41.71



**Figure 6.** Colour values of kumquat slices fresh and dried at various infrared powers

#### 4. Conclusions

In this study, infrared drying of kumquat slices is presented. Drying time decreased considerably with increase in infrared power. The drying was observed to take place entirely in the falling rate drying period and hence moisture migration to the surface is based on diffusion. To explain the drying kinetics of kumquats, five drying models were applied and fitted to the experimental data. According to the results of statistical analysis, the experimental data were well predicted by the Midilli and Kucuk model. The effective moisture diffusivity varied between  $8.31 \times 10^{-9}$  and  $1.89 \times 10^{-8}$   $\text{m}^2/\text{s}$  and increased as infrared power increased. Activation energy was estimated by a modified Arrhenius type equation and found to be 1.92 kW/kg. The colour values of  $L$ ,  $a$ ,  $b$  and  $C$  increased while those of  $\Delta E$  decreased as the power output increased.

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