Journal of Thermal Engineering, Vol. 4, No. 2, Special Issue 7, pp. 1821-1827, February, 2018
Yildiz Technical University Press, Istanbul, Turkey

INVESTIGATION OF INFRARED DRYING OF POMEGRANATE BY-PRODUCTS

İ. Doymaz[1], A. S. Kipcak[1,*]

ABSTRACT

In the present study, infrared radiation drying, representative of the innovative drying method, was chosen to perform comparative study at different infrared power levels. Infrared drying of pomegranate by-products was dried at 88, 104, 125, 146 and 167 W power levels. The results showed that the infrared power has a significant effect on the drying characteristics of pomegranate by-products. Drying time was reduced from 270 to 60 min as the infrared power level increased from 88 to 167 W. The falling-rate period proved to be the main stage of infrared drying. Three thin-layer drying models (Aghbashlo et al., Jena & Das and Midilli & Kucuk) were fitted to the experimental data. The drying data (moisture ratio versus drying time) were successfully fitted to Aghbashlo et al. model. Fick's law of diffusion was used to determine the effective moisture diffusivity, which varied between 3.296×10^{-9} to 1.431×10^{-8} m^2/s. Activation energy was estimated by a modified Arrhenius type equation as 4.424 kW/kg.

Keywords: *Infrared Drying, Pomegranate By-Product, Modelling, Effective Moisture Diffusivity, Activation Energy*

INTRODUCTION

The pomegranate, botanical name *Punica granatum*, is a fruit-bearing deciduous shrub or small tree in the family Lythraceae that grows between 5 and 8 m tall. Pomegranates are used in baking, cooking, juice blends, meal garnishes, smoothies, and alcoholic beverages, such as cocktails and wine. The pomegranate originated in the region of modern-day Iran, and has been cultivated since ancient times throughout the Mediterranean region and northern India. Today, it is widely cultivated throughout the Middle East and Caucasus region, north and tropical Africa, the Indian subcontinent, Central Asia, the drier parts of southeast Asia, and parts of the Mediterranean Basin. It is also cultivated in parts of Arizona and California. In recent years, it has become more common in the commercial markets of Europe and the Western Hemisphere [1-3].

During the industrial processing of pomegranate, large volumes of industrial wastes are produced, which have a wide range of nutritional values. Therefore, in the recent years, the attention has been focused on the industrial by-products of pomegranate that have a high potential of antioxidant and antifungal properties [4, 5]. Furthermore, the presence of abundant effective compounds has been reported in many parts of this plant such as leaves, barks, roots, peels, juice and seeds that cause high antimicrobial and antioxidant activity of them [5, 6].

Fruit by-products generally present high moisture content, which makes them perishable. One may to facilitate their subsequent use is to dry them [7]. Drying process has been used for decades in food processing industries for efficient long-term preservation of final products. The basic objective in drying food products is the removal of water from fresh product reaching a level at which microbial spoilage is avoided [8]. Hot air dying has many disadvantages such as; lower energy efficiency, long drying times, but on the other hand it has been used widely [9, 10]. Infrared (IR) heating has so many advantages compared to the widely used hot air drying. Also the equipment of IR can be compact with controllable parameters in order to control the overheating and fast heating [11].

Various agricultural and animal products have been successfully dried by the infrared application and/or by a combined infrared-assisted convection process [12-15]. However, there is no information available about infrared drying of pomegranate by-products. In this study, the thin-layer drying behaviour of pomegranate by-products in an infrared dryer was investigated, and mathematical modelling by using three thin-layer drying models available in the literature was performed. Also, the values of effective moisture diffusivity and activation energy were calculated.

This paper was recommended for publication in revised form by Regional Editor Bekir Yılbaş
[1]Department of Chemical Engineering, Yildiz Technical University, Istanbul, TURKEY
**E-mail address: skipcak@yildiz.edu.tr*
Manuscript Received 30 May 2017, Accepted 11 October 2017

MATERIALS AND METHODS

Materials

Pomegranade by-products, were provided by Döhler Natural Food & Beverage Ingredients factory located in Denizli. By-products were collected just after the pressing operation and immediately packaged and stored at 4°C. The average thickness of a pomegranate by-products were 1 cm. The initial moisture content of the pomegranate by-product was determined using the AOAC method [16] and found to be 1.729 ± 0.005 kg water/kg dry matter (d.b.).

Drying experiments were carried out in a moisture analyzer with one 250 W halogen lamp (Snijders Moisture Balance, Snijders b.v., Tilburg, Holland). The infrared drying process, the sample should be separated evenly and homogeneously over the entire pan. The drying experiments were performed at infrared power level varying from 88 to 167 W.

The samples of pomegranate by-products were removed of dryer at time intervals of 15 min during the drying process and weighted with a BB3000 model digital balance (Mettler-Toledo AG, Grefensee, Switzerland), which has an an accuracy of 0.1 g. Drying was finished when the moisture content of samples were approximately 0.005 ± 0.001 kg water /kg dry matter (d.b.). The experiments done three times and average values of the moisture contents were used.

The moisture content (*M*), drying rates (*DR*) and moisture ratio (*MR*) of pomegranate by-product were calculated using (1), (2) and (3) [17]:

$$M = \frac{m_w}{m_d} \tag{1}$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{2}$$

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{3}$$

where M is the moisture content (kg water / kg dry matter), m_w is the water content (g), m_d is the dry matter content (g), DR is the drying rate (kg water / kg dry matter × min), M_{t+dt} is the moisture content at $t + dt$ (kg water / kg dry matter), t is the drying time (min), MR is the moisture ratio (dimensionless), M_t, M_e and M_i are the moisture content at selected time, at equilibrium and the initial value in kg water / kg dry matter. The drying curves were fitted to three thin-layer drying models, which are widely used in the literature for food products (Table 1).

Table 1. Models used for fitting the experimental data

Model	Equation	Reference
Aghbashlo *et al.*	$MR = \exp\left(-\frac{k_1 \times t}{1 + k_2 \times t}\right)$	[18]
Jena & Das	$MR = a \times \exp\left(-k \times t + b \times t^{0.5}\right) + c$	[19]
Midilli & Kucuk	$MR = a\exp(-kt^n) + bt$	[20]

*k is the drying rate constant or coefficient (1/s) and a,b and c are the constants (dimensionless)

Regression analysis was conducted using the Statistica 8.0 computer programme (StatSoft Inc., Tulsa, USA). Model parameters were estimated using a non-linear regression procedure based on the Lavenberg-Marquardt algorithm. In the literature, higher R^2 values were accepted as better results [16]. R^2 equation is given in (4):

$$R^2 \equiv 1 - \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i} - \left(\frac{1}{n}\right)\sum_{i=1}^{N} MR_{exp,i}\right)} \tag{4}$$

where MR_{exp} and MR_{pre} represent experimental and predicted values of moisture ratios, respectively.

Fick's second law of unsteady state diffusion can be used to determine the moisture ratio. For longer drying periods, the equation can be given as in (5):

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2} t\right) \tag{5}$$

where D_{eff} is the effective moisture diffusivity (m^2/s), t is the time (s), L is the half-thickness of samples (m) and n is a positive integer. The effective moisture diffusivity is typically obtained by plotting *ln (MR)* versus drying time in equation 5.

Temperature is not directly measurable quantity in the infrared power level during drying process in this study. For the calculation of activation energy equation 6 is used [16]:

$$D_{eff} = D_0 \, exp\left(-\frac{E_a m}{P}\right) \tag{6}$$

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 power (W), and m is the sample weight (kg).

RESULTS AND DISCUSSION

The effect of infrared power on drying curves of pomegranate by-product during drying is shown in Figure 1. The drying curves are typical to ones for similar fruits, vegetables, by-products and pomaces. It is obvious that the moisture content decreased with drying time and infrared power. The drying time required reaching the final moisture content of samples were 270, 150, 105, 90 and 60 min at the infrared powers of 88, 104, 125, 146, and 167 W, respectively. As expected at higher infrared power level the higher heat absorption resulted in higher product temperature, higher mass transfer driving force, faster drying rate and consequently lesser drying time [14, 17, 21].

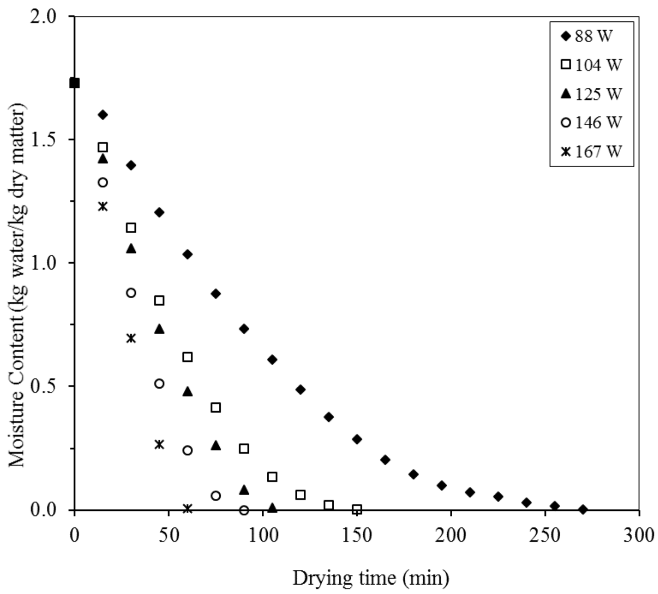

Figure 1. Moisture contents of the pomegranate by-products dried with different infrared power levels

It has been explained in the literature that the drying of food products generally follows the falling-rate period, meaning that the the last part of drying corresponds to a falling drying rate and the moisture transfer from the solid matter is explained using the Fick's second law [14, 17, 21]. In Figure 2, the drying rate vs moisture content is given for different infrared power levels. From Figure 2 it is seen that the falling-rate period proved to be the main stage of infrared drying.

In Table 1 three thin layer models created by Aghbashlo et al., Jena & Das and Midilli & Kucuk were fitted to the experimental MR with respect to drying times. The best model was selected based on the highest R^2. The results of the estimated coefficients and statistical data obtained from Aghbashlo et al., Jena & Das and Midilli & Kucuk were given in the Tables 2, 3 and 4, respectively.

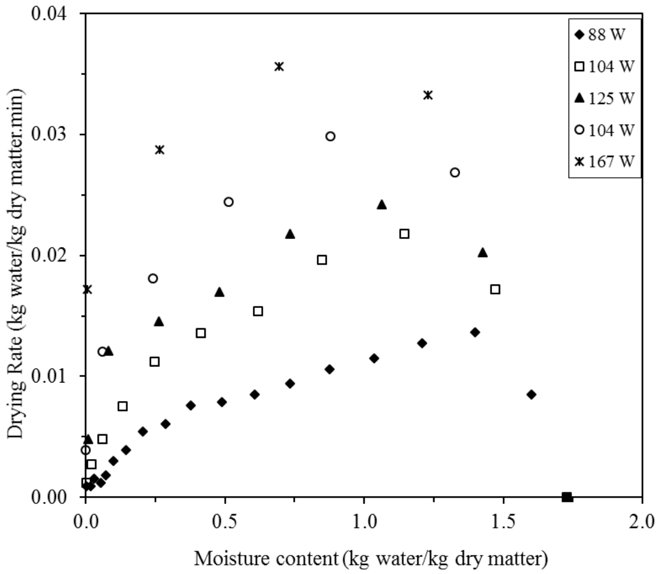

Figure 2. Drying rate curves of pomegranate by-products dried with different infrared power levels

Table 2. Estimated coefficients and statistical data obtained from Aghbashlo *et al*. model

Power (W)	k_1	k_2	R^2
88	0.007134	-0.002665	0.999104
104	0.011864	-0.004982	0.999294
125	0.012758	-0.006801	0.999380
146	0.016472	-0.008491	0.999654
167	0.018676	-0.012488	0.999778
		Average R^2	**0.999442**

In Aghbashlo et al. model the lowest and the highest R^2 values were found as 0.999104 at 88 W and 0.999778 at 167 W, respectively.

Table 3. Estimated coefficients and statistical data obtained from Jena & Das model

Power (W)	a	k	b	c	R^2
88	1.376487	0.016520	0.060306	-0.340358	0.993563
104	0.272489	0.029793	0.086654	1.291204	0.993452
125	0.271522	0.036297	0.103700	1.296538	0.988834
146	0.259459	0.048497	0.129348	1.345176	0.992141
167	0.119446	0.068202	0.183698	2.122860	0.989195
				Average R^2	**0.991437**

In Jena & Das model the lowest and the highest R^2 values were found as 0.988834 at 125 W and 0.993563 at 88 W, respectively.

In Midilli & Kucuk model the lowest and the highest R^2 values were found as 0.949948 at 146 W and 0.999631 at 104 W, respectively. Among the three models, considering the average R^2 values, Aghbashlo et al. best fits the experimental data.

Table 4. Estimated coefficients and statistical data obtained from Midilli & Kucuk model

Power (W)	a	k	n	b	R^2
88	0.996288	0.002010	1.343577	-0.000111	0.999429
104	0.997177	0.003681	1.372283	-0.000246	0.999631
125	0.999012	0.004573	1.343417	-0.000925	0.999617
146	2.473585	1.000000	0.000000	-0.011510	0.949948
167	2.621360	1.000000	0.000000	-0.017006	0.985387
				Average R^2	**0.986802**

The plot of ln(*MR*) vs. drying time (min) is shown in Figure 3.

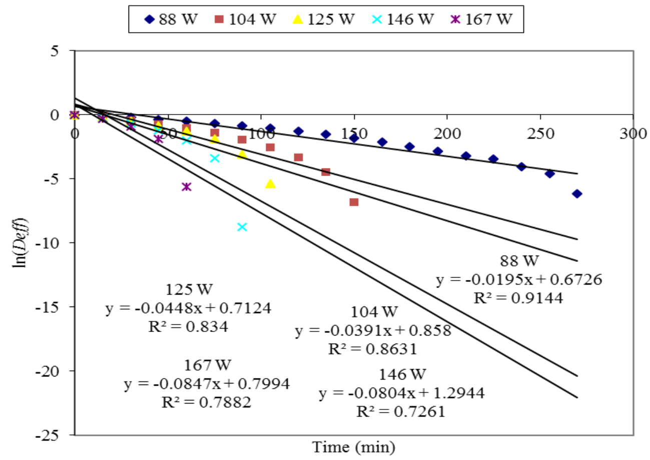

Figure 3. The plot of ln(*MR*) vs. drying time (min)

From the equations, the slope D_{eff} values are calculated as 3.296 × 10^{-09}, 6.609 × 10^{-09}, 7.573 × 10^{-09}, 1.259 × 10^{-08} and 1.413 × 10^{-08} m^2/s for the infrared power levels of 88, 104, 125, 146 and 167 W, respectively.

It is seen that D_{eff} values increased with increasing infrared power level. This phenomenon can be explained as the increase in infrared power causes a rapid temperature rise of a food product [14]. Using the obtained D_{eff} values, the plot of D_{eff} vs. infrared power level is drawn and given in Figure 4.

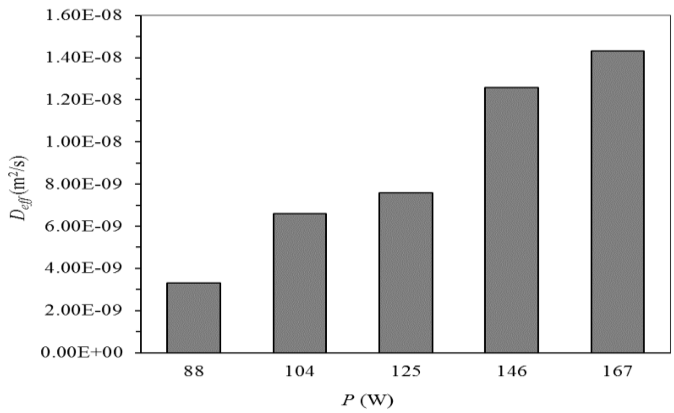

Figure 4. D_{eff} vs. *P* curve of pomegranate by-product

From the plot of ln(D_{eff}) vs. *m/P*, which is shown in Figure 5, E_a can be calculated and the estimated value of E_a are found as 4.424 kW/kg.

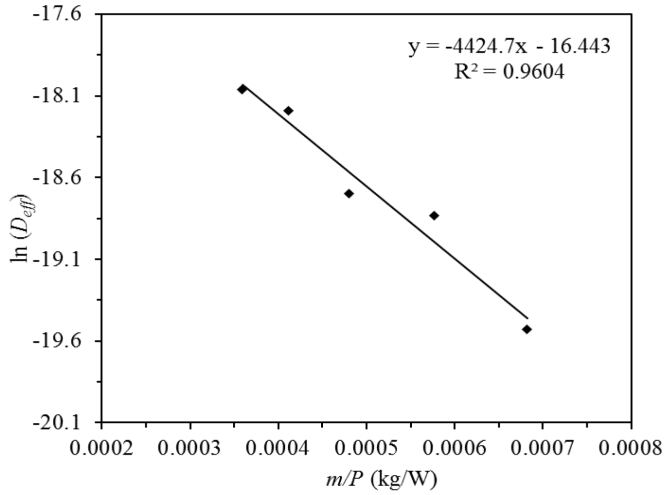

Figure 5. ln(D_{eff}) vs. *m/P* curve of pomegranate by-product

CONCLUSION

Using different drying methods, the shelf life and storage of food products can be extended In this study, the drying characteristics of pomegranate by-products is investigated using the infrared method at five different infrared power levels. The last part of drying took place in the falling-rate period. The drying time decreased with the increase in infrared power level. The *Aghbashlo et al.* model best fits the experimental results. The D_{eff} values are calculated to be between 3.296×10^{-9} to 1.431×10^{-8} m^2/s and the activation energy was estimated as 4.424 kW/kg.

REFERENCES

[1] Pomegranate (2017). Department of Plant Sciences, University of California at Davis, College of Agricultural & Environmental Sciences, Davis, CA.

[2] Morton, J. F. (1987). Fruits of warm climates. JF Morton.

[3] Pomegranate (2017). California Rare Fruit Growers. Crfg.org.

[4] Orzua, M. C., Mussatto, S. I., Contreras-Esquivel, J. C., Rodriguez, R., de la Garza, H., Teixeira, J. A., & Aguilar, C. N. (2009). Exploitation of agro industrial wastes as immobilization carrier for solid-state fermentation. Industrial Crops and Products, 30(1), 24-27.

[5] Tehranifar, A., Selahvarzi, Y., Kharrazi, M., & Bakhsh, V. J. (2011). High potential of agro-industrial by-products of pomegranate (Punica granatum L.) as the powerful antifungal and antioxidant substances. Industrial Crops and Products, 34(3), 1523-1527.

[6] Bedigian, D. (2007). Pomegranates. Ancient Roots to Modern Medicine. Medicinal and Aromatic Plants—Industrial Profiles 43.

[7] Ramos, K. K., Lessio, B. C., Mecê, A. L. B., & Efraim, P. (2017). Mathematical modeling of uvaia byproduct drying and evaluation of quality parameters. Food Science and Biotechnology, 26(3), 643-651.

[8] Calin-Sanchez, A., Figiel, A., Wojdyło, A., Szarycz, M., & Carbonell-Barrachina, A. A. (2014). Drying of garlic slices using convective pre-drying and vacuum-microwave finishing drying: kinetics, energy consumption, and quality studies. Food and Bioprocess Technology, 7(2), 398-408.

[9] Feng, H., & Tang, J. (1998). Microwave finish drying of diced apples in a spouted bed. Journal of Food Science, 63(4), 679-683.

[10] Pan, Z., Khir, R., Godfrey, L. D., Lewis, R., Thompson, J. F., & Salim, A. (2008). Feasibility of simultaneous rough rice drying and disinfestations by infrared radiation heating and rice milling quality. Journal of food engineering, 84(3), 469-479.

[11] Sakai, N., & Hanzawa, T. (1994). Applications and advances in far-infrared heating in Japan. Trends in Food Science & Technology, 5(11), 357-362.

[12] Adak, N., Heybeli, N., & Ertekin, C. (2017). Infrared drying of strawberry. Food chemistry, 219, 109-116.

[13] Celma, A. R., Cuadros, F., & López-Rodríguez, F. (2009). Characterisation of industrial tomato by-products from infrared drying process. Food and Bioproducts Processing, 87(4), 282-291.

[14] Doymaz, I., Kipcak, A. S., & Piskin, S. (2015). Characteristics of Thin-layer Infrared Drying of Green Bean. Czech Journal of Food Science, 33(1).
[15] Nowak, D., & Lewicki, P. P. (2005). Quality of infrared dried apple slices. Drying Technology, 23(4), 831-846.
[16] Arlington, V. A. Association of official analytical chemists (AOAC): official methods of analysis of official analytical chemists international.
[17] Kipcak, A. S. (2017). Microwave drying kinetics of mussels (Mytilus edulis). Research on Chemical Intermediates, 43(3), 1429-1445.
[18] Aghbashlo, M., Kianmehr, M. H., Khani, S., & Ghasemi, M. (2009). Mathematical modelling of thin-layer drying of carrot. International Agrophysics, 23(4), 313-317.
[19] Jena, S., & Das, H. (2007). Modelling for vacuum drying characteristics of coconut presscake. Journal of Food Engineering, 79(1), 92-99.
[20] Balbay, A., Şahin, Ö., & Ülker, H. (2013). Modeling of convective drying kinetics of pistachio kernels in a fixed bed drying system. Thermal science, 17(3), 839-846.
[21] Doymaz, I., Kipcak, A. S., & Piskin, S. (2015). Microwave Drying of Green Bean Slices: Drying Kinetics and Physical Quality. Czech Journal of Food Science, 33(4).