Jordan Journal of Agricultural Sciences, Volume **13**, No.**3** 2017

Mathematical Modeling of the Kinetics of Thin-Layer Infrared Drying of Lemon

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ABSTRACT

In this work, mathematical modeling of infrared drying of thin-layer lemon slices with 5±1 mm thickness was investigated. Thin-layer drying was conducted under four different drying temperatures (100, 125, 150 and 175 °C) at absolute humidity of 0.6 ± 0.02 g of water/kg of dry air. The results revealed that the drying process occurred in falling rate period over the drying time. Moisture transfer from lemon slices was described by Fick's diffusion model. The effective diffusivity for lemon slices was within the range of 9.9 $\times 10^{-10}$ to 2.76×10^{-9} m^2/s over the temperature range. The activation energy was found to be 87.61 kJ/mol indicating the effect of temperature on diffusivity. Eight well-known thin-layer drying models were fitted to the drying experimental data of lemon slices, implementing non-linear regression analysis techniques. Based on the statistical analysis using coefficient of determination (R^2) and root mean square error (RMSE), it was concluded that the best model in terms of fitting performance for infrared drying of lemon slices at all selected temperatures were Wang and Sing model.

Keywords: Lemon, Mathematical modeling, Infrared drying, Thin-layer.

INTRODUCTION

Lemons [*Citrus lemon* (L.) Burms.f] have many important natural chemical components, including citric acid, ascorbic acid, minerals, flavonoids and essential oils. Dried lemons are widely produced in Iran and other Mediterranean countries, such as Egypt and Turkey. In this functional product, lemon peel is important for technological and nutritional aspects. The peel is a by-product of lemon juice processing, with a high potential use. Two different tissues are found in what is colloquially called lemon peel, flavedo and albedo. Flavedo is the peel's outer layer, whose colour varies from green to yellow. It is a rich source of essential oils (Brat et al., 2001), which have been used since ancient times by the flavour and fragrance industry (Vekiari et al., 2002). Albedo is the major component of lemon peel, and is a spongy and cellulosic layer laid under flavedo. The thickness of the albedo fluctuates according to several variables such as variety and degree of ripeness. Albedo has a high dietary fiber content, and if added to new meat products permits to formulate healthier products like beef burgers, dry cured sausages (Aleson-Carbonell et al., 2005) and bologna (Fernandez-Gines et al., 2004). Furthermore, the presence of associated bioactive compounds (flavonoids and vitamin C) with antioxidant properties in fresh lemon albedo involves healthier benefits than other sources of dietary fiber (Marin et al., 2002). Moisture content reduction is necessary to increase shelf life and assure all-year-round supply. Drying also facilitates handling conditions, reducing storage and

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Received on 5/5/2014 and Accepted for Publication on 5/10/2016.

transport costs (Aleson-Carbonell et al., 2005).

Infrared (IR) is the most efficient form of electromagnetic radiation for heat transfer (Das et al., 2003); the material is dried directly by absorption of IR energy. Transmission of electromagnetic radiation does not require a medium for its propagation, unlike convection drying, in which heat transfer is through the air. The effect of IR on foodstuffs depends mainly on three parameters: the physicochemical nature of the product, its water content and shape. Infrared drying has been investigated as potential method for obtaining high quality dried foodstuffs including fruits, vegetables and grains (Togrul, 2006). Although, IR heating provides a rapid means of heating and drying, it is attractive only for surface heating application (Ziaforoughi et al., 2016).

Mathematical modeling is a very useful tool to quickly and inexpensively ascertain the effect of different system and process parameters on the outcome of a process (Yousefi et al., 2013; Khodabakhsh Aghdam et al., 2015). Mathematical modeling of thin-layer drying is important for optimum management of operating parameters and prediction of performance of the drying system (Jain and Pathare, 2004). Numerous mathematical (empirical and semi-empirical) models have been proposed to define the drying behavior of food and agricultural products. The theoretical model depends on the physical characteristics of the food (Yousefi et al., 2013). The empirical model presents a direct relationship between average moisture and drying time by means of regression analysis (Ozdemir and Devres, 1999). Semi-theoretical is a trade off between the theoretical and empirical models, and is derived from Fick's second law of diffusion (Zomorodian and Moradi, 2010). It is used in the form of the Page model, the Modified Page model, the Henderson model and other models. Kingsly and Singh (2007) studied thin-layer drying of pomegranate arils in a cabinet drier at drying temperatures of 50, 55 and 60 °C. They reported that the Page model satisfactorily represented the drying characteristics of pomegranate arils than other models. Mathematical modeling technique can be used as a useful tool to design and control the IR heating system appropriately. As for food operations, many IR heating models have been provided (Datta and Ni, 2002; Shilton et al., 2002), and these predictions were conducted by solving the heat and mass transfer equation as a deterministic model with appropriate boundary and initial conditions.

Although many mathematical models have already been proposed to describe the drying process, of which thin layer-drying models have widely been in use (Hasan and Hobani, 2000), very little

information is available for modeling of high temperature drying of lemon under infrared drying conditions. The objectives of this study are (1) to determine the effective moisture diffusivity and activation energy of lemon during drying using infrared as heating source, and its dependence on temperature; (2) to find the most appropriate thin layer-drying model for describing the infrared drying behavior of lemon.

2. Materials and methods

2.1. Sample preparation

Lemon fruits with uniform shape, colour and size and without any defection were purchased from a local market and stored in a refrigerator at 4±1°C before they were subjected to the drying process. Then, they were allowed to sit at room temperature (24±1ºC) to uniform their temperature one hour before starting the experiments. For all experiments, lemons were washed and then cut to halves and sliced into5±1mm thickness. The initial moisture content of lemon was 525±2% dry basis (d.b.).

2.2. Infrared (IR) Dryer Setup

An infrared dryer with controllable radiation power was built. A circular 250-Watt Halogen Heating Tube (O-Yate Lighting Electrical Co., China) is controlled with an accurate dimmer through voltage regulating. The power of the halogen lamp is measured using a power meter (model UT230A, UNI-T, China) with a sensitivity of ±0.1 Watt. The upper side of the dryer was exposed to ambient, which means a natural convection cooled down the sample. Also, there were two openings in the lower side of the dryer to make a natural stream possible. Room air temperature and humidity were kept at 23±1 ˚C and 35±1% with an HVAC system. An insulated tray was located 157±1 mm below the emitter to exclude conduction heat transfer from the drying process; therefore, only radiation and natural convection were involved in heat transfer during the drying process. Lemon samples were placed in a single layer on the drying tray and heated from one side. Surface temperatures were measured with a thermometer (model MT-29/1, PHYSITEMP, USA). Measurements were every 5 minutes for the first one hour and every 20 minutes (because of slow drying rate at the end of drying process) until end of drying.

2.3. Experimental procedure

2.3.1. Infrared drying process

One layer of the lemon samples was placed in the infrared dryer at three temperatures of 100, 125, 150 and 175 °C for infrared drying process and weight – time data were recorded until achieving to 11±1% (d.b.) moisture content from the initial moisture content of 525±2% (d.b.). The MR *vs.* drying time curve was obtained for each drying temperature.

2.3.2. Mathematical modeling

Eight well-known models of thin-layer drying described in Table 1were investigated to find the most suitable drying model for the drying process of lemon. The MR was defined by:

$$MR = (M - M_e)/(M_0 - M_e) \quad [1]$$

Where, M and M_0 are the moisture content of the samples at any drying time and initial moisture content, respectively. The moisture ratio equation was simplified to M/M_0 as the value of M_e (equilibrium moisture content) is relatively small compare to M or M_0 (Akgun and Doymaz, 2005; Doymaz, 2004). In a general manner, the performance of a model is evaluated based on the comparison between the computed output (predicted) and input (experimental) data. The obtained predicted data for each model is evaluated using the coefficient of determination (R^2) and root mean square error (RMSE) (Eqs. 2 and 3). A model with the maximum of R^2 and the minimum of RMSE shows the best performance (Kingsly and Singh, 2007):

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

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2\right]^{1/2} \quad [3]$$

Where, $MR_{exp.i}$ is the experimental moisture ratio at observation i, $MR_{pre,i}$ is the predicted moisture ratio at this observation, N is number of experimental data points, $\overline{MR}_{exp}$ and $\overline{MR}_{pre}$ are the average of sum of the $MR_{exp.i}$ and $MR_{pre,i}$, respectively.

Table 1.Mathematical models for thin-layer drying

Model name	Model equation	References
Newton	$MR = \exp(-kt)$	Westerman and White, 1973
Page	$MR = \exp(-kt^n)$	Guarte, 1996
Modified Page	$MR = \exp(-kt)^n$	Yaldiz et al., 2001
Henderson and Pabis	$MR = a\exp(-kt)$	Yagcioglu et al., 1999
Logarithmic	$MR = a\exp(-kt) + c$	Yaldiz et al., 2001
Two-term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Rahman, 1998
Wang and Sing	$MR = 1 + at + bt^2$	Ozdemir and Devres, 1999
Midilli et al.	$MR = a\exp(-kt^n) + bt$	Sacilik et al., 2006

2.4. Statistical analysis

The drying process at each temperature was performed in triplicate. Mathematical modeling was done using curve fitting toolbox of MATLAB programming software (the Math Works, Inc., R2013a). Analysis of variance (ANOVA) was used to find out any significant difference between the moisture content of the samples affected by the drying temperatures at confidence level of 95%.

3. Results and discussions

3.1. Infrared drying

As expected, increasing temperature of infrared dryer reduced the drying time (Figs. 1, 2 and 3). At higher temperature, the drying process occurred in a shorter time due to the quick removal of moisture. The decrease in drying time with increase in drying temperature may be due to increase in water vapor pressure within the lemon sampels, which increased the migration of moisture, especially when the drying occurs only in falling rate period (Yousefi et al., 2013). Vergara et al. (1997) reported that the drying process of apple purees at 50, 60 and 70 °C occurred at least in one falling rate period. The moisture ratio of lemon reduced exponentially as the drying time increased. Continuous decrease in moisture ratio indicates that, diffusion governed the internal mass transfer (Haghi and Amanifard, 2008). As expected, higher drying temperature decreased the moisture ratio faster. During infrared drying, the moisture content of lemons amples at all the drying temperature was brought to 11± 0.1% (d.b.). It is found that there was no constant rate drying period in the drying kinetics of lemon samples, and all drying process occurred in the falling rate period (Figs. 1, 2 and 3). This matter indicates that diffusion is the controlling physical mechanism regulating moisture transfer in the sample slices. The similar results were reported in the case of hot-air drying by Kaymak-Ertekin (2002) for green and red peppers, Sogi et al. (2003) for tomato seeds and Doymaz (2007) for pumpkin and in the case of infrared drying by Ziaforoughi et al. (2016) for quince. As it can be seen in Figs.1, 2 and 3, there is a significant difference between three drying temperatures ($p<0.05$). In the case of whole lemon, drying time has been reduced approximately to quarter by increasing of temperature from 100 ˚C to 150 °C but additional increase is impossible because of the whole lemon inner pressure of vapour increase suddenly and causes to rupture of lemon peel. Figure 3 shows the effect of drying temperature and drying time on moisture ratio of lemon slices. As illustrated, there is a considerable difference in drying time compare to whole lemon and lemon halves. This phenomenon indicates that infrared radiations are most proper for surface treatment, therefore lemon slices shows best result of drying process under infrared condition.

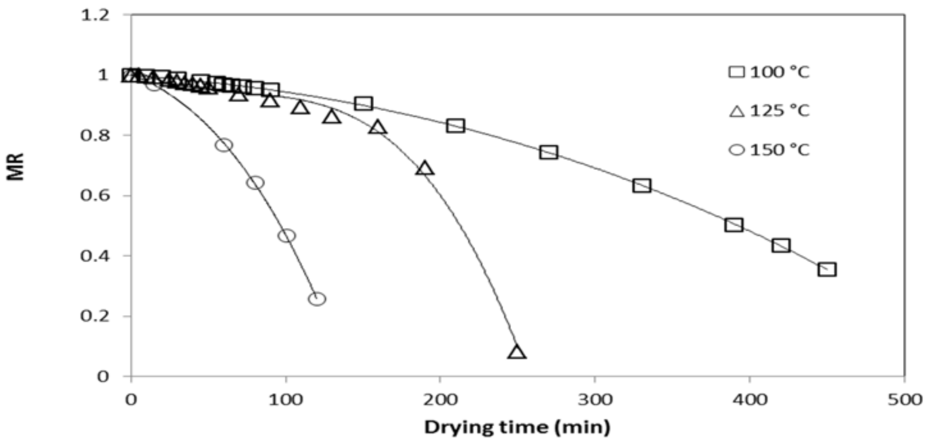

Fig. 1. Effect of drying temperature and drying time on moisture ratio of whole lemon.

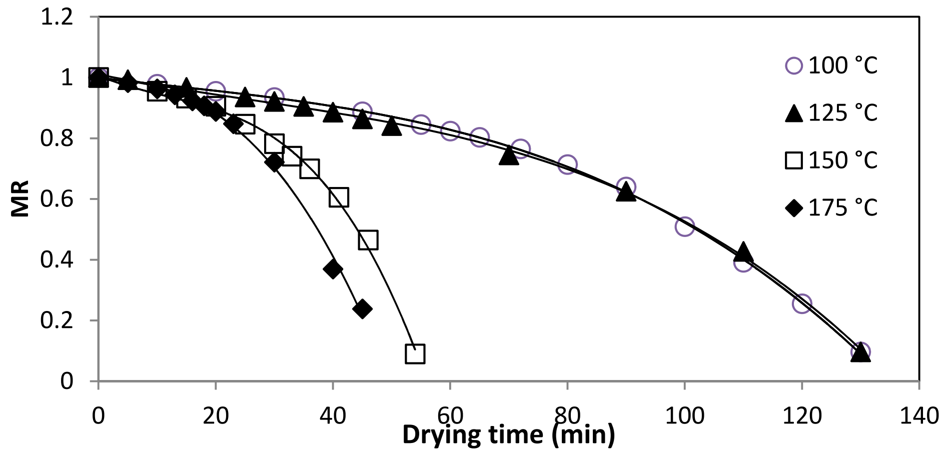

Fig. 2. Effect of drying temperature and drying time on moisture ratio of lemon halves.

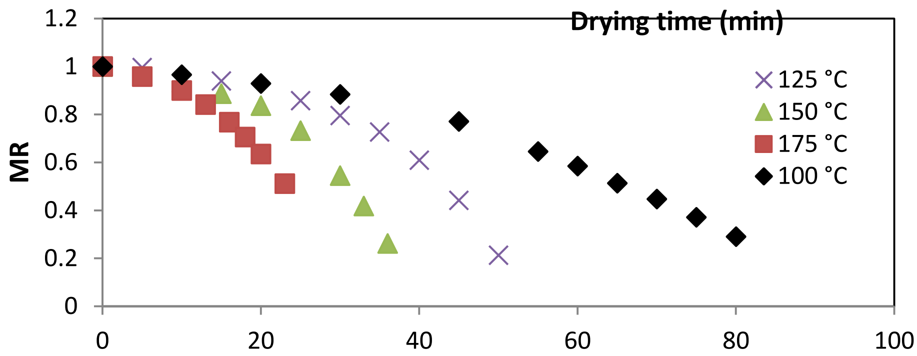

Fig. 3. Effect of drying temperature and drying time on moisture ratio of lemon slices.

3.2. Mathematical modeling

The MR values were fitted against the drying time at each temperature by applying the non-linear regression analysis technique. The best model for each treatment was obtained using comparison of statistical parameters of R^2 and RMSE. According to Table 2, Wang and Sing model was the best among the mathematical models in fitting the experimental data, which can be used to predict the drying behavior of lemon slices under the mentioned conditions. Figure 3 shows the good coincidence between experimental and predicted MR obtained from the best model at each drying temperature, which banded around the straight line *(X=Y)*; that proved the feasibility of the selected model in describing the drying behavior of thin-layer papaya slices. Yousefi et al. (2012) reported that two-term model was the best mathematical model to describe thin-layer hot air drying of papaya fruit without any pretreatments in a cabinet drier. Zomorodian and Moradi (2010) found that Midilli model had the closest results to the experimental data for forced convective indirect model type thin layer solar drying of *Cuminumcyminum* (R^2=0.994, RMSE=0.0225). Karaaslan and Erdem (2014) declared that Midilli-Kucuk model (among the mathematical models used) gave the best prediction in the case of convective drying of orange slices at 100, 150 and 200 °C.

Table 2. Statistical results obtained from the selected models

Model	Temperature (ºC)	R^2	RMSE
Newton	**100**	0.9148	0.0610
	125	0.7703	0.1358
	150	0.7900	0.1310
	175	0.8817	0.0629
Page	**100**	0.9945	0.0146
	125	0.9793	0.0371
	150	0.9850	0.0328
	175	0.9950	0.0119
Modified Page	**100**	0.9148	0.0610
	125	0.7703	0.1359
	150	0.7900	0.1310
	175	0.8817	0.0629
Henderson and Pabis	**100**	0.9088	0.7451
	125	0.7548	0.1255
	150	0.7712	0.1197
	175	0.8737	0.0557
Two- term	**100**	0.9088	0.0503
	125	0.7601	0.1245
	150	0.9207	0.0707
	175	0.9289	0.418

Model	Temperature (°C)	R^2	RMSE
	100	0.9437	0.0413
Logarithmic	**125**	0.8378	0.1016
	150	0.8639	0.0916
	175	0.9172	0.0450
	100	0.9977	0.0086
Wang and Singh	**125**	0.9854	0.0310
	150	0.9885	0.0270
	175	0.9983	0.0066
	100	0.9746	0.0286
Midilli et al.	**125**	0.8307	0.1078
	150	0.8196	0.1094
	175	0.9696	0.0273

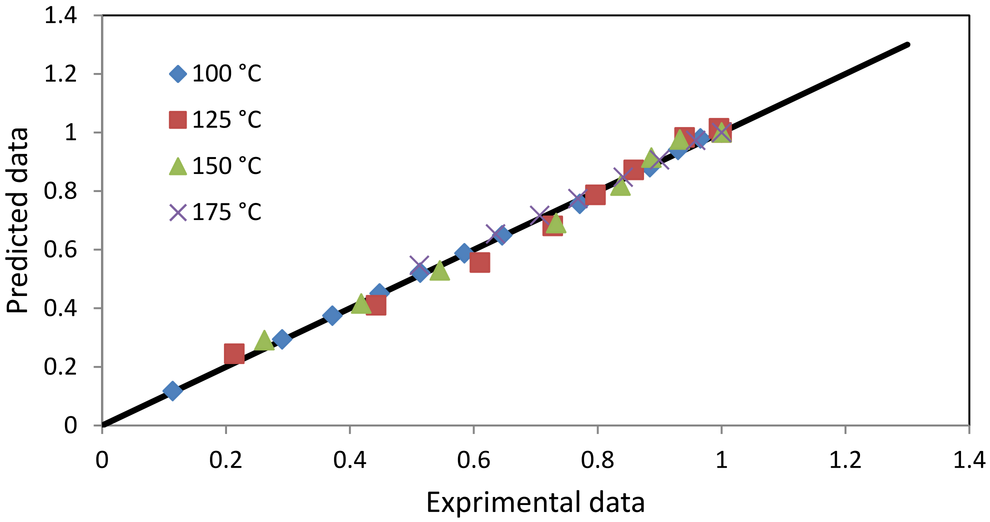

Fig. 4. Comparison of the experimental and predicted MR from Wang and Sing model.

3.3. Calculation of effective diffusivity

From the experimental data, internal mass transfer resistance was observed because of falling rate drying period. Fick's diffusion equation analyzed the drying data in the falling rate period. Crank (1975) solved this equation and introduced the following equation, which can be used for slab geometry with uniform initial moisture diffusion, constant diffusivity and insignificant shrinkage:

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

where, D_{eff} is the effective diffusivity (m^2/s); n is positive integer, t is drying time, and L is the half thickness of the slab in samples (m). In practice, only the first term in Eq.

(4) is used yielding:

$$MR = \frac{8}{\pi^2}\exp(-\frac{\pi^2 D_{eff} t}{4L^2}) \quad [5]$$

As it is obvious, D_{eff} can be calculated from the slopeof Eq. (5) using natural logarithm plot of MR versus drying time.

The calculated D_{eff} values for different drying temperatures are shown in Fig. 4. D_{eff} value for lemon slices increased with air temperature. This value for lemon slices was within the range of 9.9 $\times 10^{-10}$ to 2.76×10^{-9} m^2/sover the temperature range. Madamba et al. (1996) reported that the D_{eff} value for food materials is within the range of 10^{-11} to 10^{-9}. The obtained results were in agreement with the results of Kaleemullah and Kailappan (2005), Sacilik et al. (2006) and Doymaz (2007).

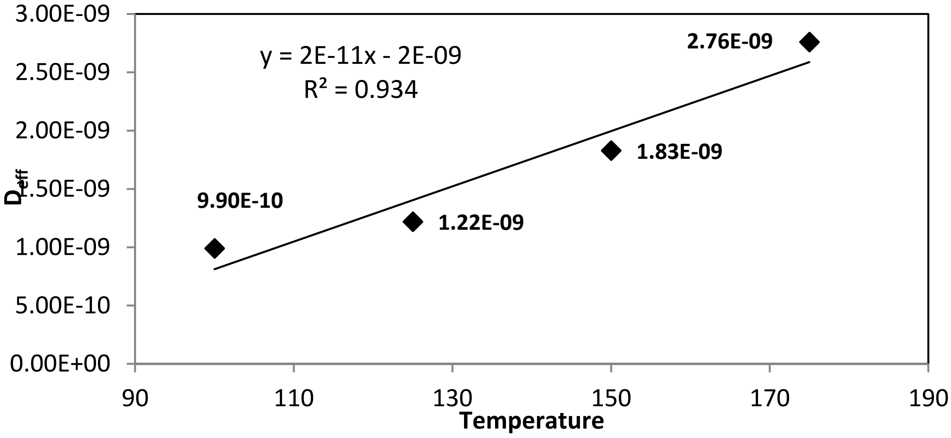

Fig. 5. Effect of drying temperature on the effective moisture diffusivity in lemon slices.

The effective moisture diffusivity represents overall mass transport of moisture in the material, including liquid diffusion, vapor diffusion, or any other possible mass transfer mechanism (Afzal and Abe, 1998). The higher effective diffusivity for thicker slices may be due to the decrease in activation energy when slice thickness increases. Afzal and Abe (1998) suggested that decreased activation energy with increased potato slice thickness indicated that the penetration of IR radiation into biological materials causes the water molecule to vibrate. Therefore, the molecules require less energy to transfer from a porous material in the mobilized state (Afzal and Abe, 1998).

3.4. Calculation of activation energy

From the Arrhenius-type relationship, the dependence of D_{eff} can be explained (Simal et al., 1996). This matter is shown in the following equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \quad [6]$$

Where D_0 is the pre-exponential factor of Arrhenius equation (m^2s^{-1}), E_a is the activation energy (kJ/mol), T is the drying temperature (°C) and R is the gas constant (kJ/(mol.K)).

The E_a can be calculated from the slope of the plot on ln(*Deff*) vs. 1/(T+273.15) (Fig. 5). This value was 87.61(kJ/mol) for lemon slices. This obtained value was lower than the E_a of green peppers drying (51.4 kJ/ mol) (Kaymak-Ertekin, 2002), mint drying (82.93 kJ/mol) (Park et al., 2002) and higher than that of red chillies drying (24.47 kJ/ mol) (Kaleemullah and Kailappan, 2005).

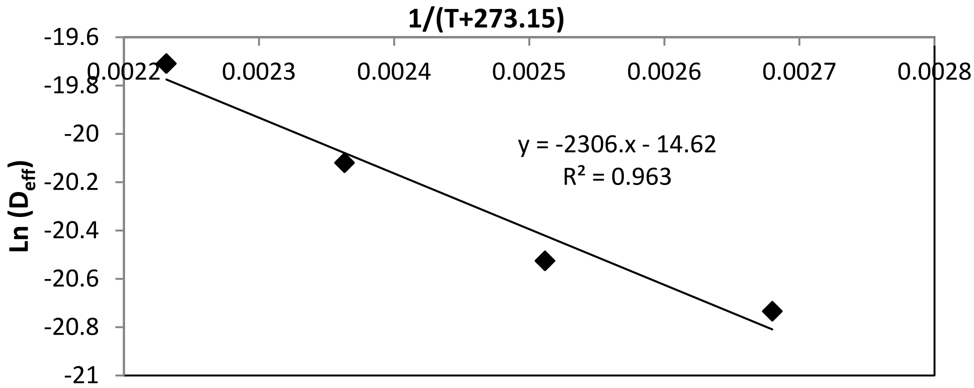

Fig.6. Influence of drying temperature on the effective diffusivity.

4. Conclusion

In this study, infrared drying kinetics of lemon samples at four levels of drying temperatures in an infrared dryer was investigated. Like most of food materials, lemon samples had not constant drying rate and drying process entirely occurred in falling rate period. Wang and Singh model revealed the highest performance to predict MR during the drying process at all the drying temperatures. The obtained effective diffusivity (9.9×10^{-10} to 2.76×10^{-9} m^2/s) indicted the high sensitivity of D_{eff} to the temperatures selected. The activation energy for lemon slices was found to be 87.61kJ/mol using Arrhenius-type equation.

REFERENCES

Afzal, T. M., Abe, T., 1998, Diffusion in potato during far infrared radiation drying. ***Journal of Food Engineering***, 37: 353–365.

Akgun, N., Doymaz, I., 2005, Modeling of olive cake thin-layer drying process. ***Journal of food Engineering***, 68: 455-461.

Aleson-Carbonell, L., Fernandez-Lopez, J., Perez-Alvarez, J. A., Kuri, V., 2005, Characteristics of beef burger as influenced by various types of lemon albedo. ***Innovative Food Science and Emerging Technologies***, 6: 247–255.

Aleson-Carbonell, L., Fernandez-Lopez, J., Sayas-Barbera, E., Sendra, E., & Perez-Alvarez, J.A., 2003, Utilization of lemon albedo in dry-cured sausages. ***Journal of Food Science***, 68: 1826–1830.

Brat, P., Olle, D., Gancel, A. L., Reynes, M., Brillouet, J. M., 2001, Essential oils obtained by flash vacuum-expansion of peels from lemon, sweet orange, mandarin and grapefruit. ***Fruits,*** 56: 395–402.

Crank, J., 1975, The Mathematics of Diffusion, second ed. Oxford University Press, London.

Das, I., Bal, S., and Das, S.K., 2003, Optimization of the vibration – aided infrared heating process using response surface methodology: An application to the drying and parboiling of high moisture paddy. American Society of Agricultural and Biological Engineers, St. Joseph, Michigan www.asabe.org

Datta, A. K., and Ni, H., 2002, Infrared and hot-air-assisted microwave heating of foods for control of surface moisture. ***Journal of Food Engineering,*** 51: 355–364.

Doymaz, I., (2007). The kinetics of forced convective air-drying of pumpkin slices. ***Journal of Food Engineering***, 79, 243–248.

Doymaz, I., 2004, Pretreatment effect on sun drying of mulberry fruits (*Morusalba* L.). ***Journal of Food Engineering***, 65: 205–209.

Guarte, R., 1996, Modeling the drying behavior of copra and development of a natural convection dryer for production of high quality copra in the Philippines. Ph.D. dissertation, 287.Hohenheim University, Stuttgart, Germany.

Haghi, A. K., Amanifard, N., 2008, Analysis of heat and mass transfer during microwave drying of food products. ***Brazilian Journal of Chemical* Engineering**, 25: 491-501.

Hasan, H.B., Hobani, A.I., 2000, Thin layer drying of dates. ***Journal of Food Process Engineering,*** 23: 177-183.

Jain, D., and Pathare, P.B., 2004, Selection and evaluation of thin layer drying models for infrared radiative and convective drying of onion slices. ***Biosystems Engineering*** 89: 289–296.

Kaleemullah, S., Kailappan, R., 2005, Drying kinetics of red chillies in rotary dryer. ***Biosystems Engineering***, 92: 15–23.

Karaaslan, S., Erdem, T., 2014, Mathematical modeling of orange slices during microwave, convection, combined microwave and convection drying. ***Turkish Journal of Agricultural and Natural Sciences***, 1: 143-149.

Kaymak-Ertekin, F., 2002, Drying and rehydrating kinetics of green and red peppers. ***Journal of Food Science,*** 67: 168–175.

Kaymak-Ertekin, F., Sultanoglu, M., 2000, Modelling of mass transfer during osmotic dehydration of apples. ***Journal of Food Engineering***, 46: 243–250.

Khodabakhsh Aghdam, S., Yousefi, A.R., Mohebbi, M., Razavi, S.M.A., Orooji, A., Akbarzadeh-Totonchi, M.R., 2015, Modeling for drying kinetics of papaya fruit using fuzzy logic table look-up scheme. ***International Food Research Journal***, 22: 1234-1239.

Kingsly, A.R.P., Singh, D.B., 2007, Drying kinetics of pomegranate arils. ***Journal of Food Engineering,*** 79,741–744.

Madamba, P.S., Driscoll, R.H., Buckle, K.A., 1996, The thin-layer drying characteristics of garlic slices. ***Journal of Food Engineering,*** 29: 75–97.

Marın, F. R., Frutos, M. J., Perez-Alvarez, J. A., Martınez-Sanchez, F., Del Rio, J. A., 2002, Flavonoids as nutraceuticals; structural related antioxidant properties and their role on ascorbic acid preservation.In Atta-Ur-Rahman (Ed.), Studies in natural products chemistry (pp. 741–778). Amsterdam, Holland: Elsevier.

Midilli, A., Kucuk, H., Yapar, Z.A., 2002, New model for single-layer drying. ***Drying Technology,*** 20: 1503-1513.

Ozdemir, M., Devres, Y., 1999, The thin layer drying characteristics of hazelnuts during roasting. ***Journal of Food Engineering***, 42: 225-233.

Ozdemir, M., Devres, Y., 1999, The thin layer drying characteristics of hazelnuts during roasting. ***Journal of Food Engineering,*** 42: 225-233.

Park, K.J., Vohnikova, Z., Brod, F.P.R., 2002, Evaluation of drying parameters and desorption isotherms of garden mint leaves (*Menthacrispa* L.). ***Journal of Food Engineering***, 51: 193–199.

Rahman, M., 1998, Desorption isotherm and heat pump drying kinetics of peas. ***Food International Research***, 30: 485-491.

Sacilik, K., Keskin, R., Elicin, A., 2006, Mathematical modeling of solar tunnel drying of thin layer organic tomato. ***Journal of Food Engineering***, 73: 231-238.

Sharma, G.P., Prasad, S., Datta, A.K., 2003, Drying kinetics of garlic cloves under convective drying conditions. ***Journal of Food Science and Technology***, 40: 45–51.

Simal, S., Mulet, A., Tarrazo, J., Rosello, C., 1996, Drying models for green peas. ***Food Chemistry,*** 55: 121–128.

Sogi, D.S., Shivhare, U.S., Garg, S.K., Bawa, A.S., 2003, Water sorption isotherms and drying characteristics of tomato seeds. ***Biosystems Engineering,*** 84: 297–301.

Togrul, H., 2006, Suitable drying model for infrared drying of carrot. ***Journal of Food Engineering***, 77: 610-619.

Vekiari, S. A., Protopadakis, E. E., Papadopoulou, P., Papanicolau, D., Panou, C., Vamvakias, M., 2002, Composition and seasonal variation of the essential oil from leaves and peel of a cretan lemon variety. ***Journal of Agricultural and Food Chemistry***, 50: 147–153.

Vergara, F., Amezaga, E., Barcenas, M. E., Welti, J., 1997, Analysis of the drying processes of osmotically dehydrated apple using the characteristic curve model. ***Drying Technology,*** 15: 949-963.

Westerman, P., White, W., 1973, Relative humidity effect on the high temperature drying of shelled corn. ***Transaction of American Society of Agricultural Engineering***, 16: 1136-1139.

Yagcioglu, A., Degirmencioglu, A., &Cagatay, F., 1999, Drying characteristics of laurel leaves underdifferent drying conditions. In proceedings of the 7th international congress on agricultural mechanization and energy. (pp. 565-569), Adana, Turkey.

Yaldiz, O., Ertekin, C., Uzun, H.I., 2001, Mathematical modeling of thin layer solar drying of Sultana grapes. ***Energy,*** 42: 167-171.

Yousefi, A.R., Asadi, V., Nassiri, S., Niakousari, M., KhodabakhshAghdam, Sh., 2012, Comparison of mathematical and neural network models in the estimation of papaya fruit moisture content. ***Philippine Journal of Agricultural Scientist***, 95: 192-198.

Yousefi, A.R., Niakousari, M., Moradi, M, 2013, Microwave assisted hot air drying of papaya (*Carica papaya* L.) pretreated in osmotic solution. ***African Journal of Agricultural Research***, 8: 3229-3235.

Ziaforoughi, A., Yousefi, A.R., Razavi, S.M.A., 2016, A comparative modeling study of quince infrared drying and evaluation of quality parameters. ***International Journal of Food Engineering***, DOI: 10.1515/ijfe-2016-0074.

Zomorodian, A., Moradi, M., 2010, Mathematical modeling of forced convection thin layer solar drying for *Cuminumcyminum*. ***Journal of Agriculture Science and Technology***, 12: 401-408.

النمذجة الرياضية للتجفيف بالأشعة تحت الحمراء لشرائح الليمون

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ملخص

في هذا البحث، تم دراسة النمذجة الرياضية للتجفيف بالأشعة تحت الحمراء لشرائح الليمون ذات الطبقة الرقيقة بسمك 5 ± 1 مم. تم تجفيف طبقة رقيقة تحت أربعة درجات حرارة تجفيف مختلفة (100، 125، 150 و 175 درجة مئوية) عند رطوبة مطلقة 0.6 ± 0.02 غرام من الماء / كجم من الهواء الجاف. وأظهرت النتائج أن عملية التجفيف حدثت في مرحلة السقوط خلال فترة التجفيف. تم وصف نقل الرطوبة من شرائح الليمون عن طريق نموذج انتشار فيكس. كان الانتشار الفعال لشرائح الليمون في حدود 9.9 × 10−10 إلى 2.76 × 10−9 متر مربع / ثانية على مدى درجة الحرارة الذي تمت الدراسه عليه. تم حساب طاقة التنشيط لتكون 87.61 كج / مول مما يدل على تأثير درجة الحرارة على الانتشار. وتم استخدام ثمانية نماذج تجفيف طبقة رقيقة معروفة على تجفيف البيانات التجريبية لشرائح الليمون، وتنفيذ تقنيات تحليل الانحدار غير الخطية. واستنادا إلى التحليل الإحصائي باستخدام معامل التحديد (R^2) وخطأ متوسط الجذر (MSE)، استنتج أن أفضل نموذج من حيث الأداء لتجفيف الأشعة تحت الحمراء لشرائح الليمون في جميع درجات الحرارة المختارة كان نموذج Wang and Sing" .

الكلمات الدالة: الليمون، النمذجة الرياضية، التجفيف بالأشعة تحت الحمراء، رقيقة، طبقة.

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تاريخ استلام البحث 2014/5/5 وتاريخ قبوله 2016/10/5.