Journal of Applied Science and Agriculture, 9(16) October 2014, Pages: 32-39

AENSI Journals

Journal of Applied Science and Agriculture

ISSN 1816-9112

Journal home page: www.aensiweb.com/JASA

The Kinetics of Infrared Drying of Lemon (Citrus Lemon (L.) Burms. F)

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ARTICLE INFO

Article history:
Received 11 June 2014
Received in revised form 25 July 2014
Accepted 20 September 2014
Available online 1 October 2014

Keywords:
Lemon Mathematical modeling
Infrared drying Thin-layer
Activation energy

ABSTRACT

Background: The dried lemons have a sharp flavour and are very aromatic which widely used in many foods. **Objective:** In this study, 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. **Results:** It was found 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 ×10-10 to 2.76×10-9 m2/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 (R²) 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.

To Cite This Article: Akram Heidari, Masoud Taghizadeh, Elham Mahdian and Amir Salari, The Kinetics of Infrared Drying of Lemon (Citrus Lemon (L.) Burms.F). ***J. Appl. Sci. & Agric.,*** *9(16): 32-39, 2014*

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, among them 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). 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 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.

Mathematical modeling is a very useful tool to quickly and inexpensively as certain the effect of different system and process parameters on the outcome of a process. 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

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define the drying behavior of food and agricultural products. The theoretical model depends on the physical characteristics of food. 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 tradeoff between the theoretical and empirical models, and is derived from Fick's second law of diffusion. 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. To design and control the IR heating system appropriately, a mathematical modeling technique becomes one of the most useful tools. 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.

Nomenclature	Definition
M	Moisture content at any time of drying
M_e	Equilibrium moisture content
M_0	Initial moisture content
MR	Moisture ratio
$MR_{pre,i}$	Ith predicted MR
$MR_{\exp,i}$	Ith experimentally observed MR
N	Number of observations
R^2	Coefficient of determination
RMSE	Root of mean square error
D_{eff}	Effective diffusivity
D_0	pre-exponential factor of Arrhenius equation
E_a	Activation energy
n	Positive integer
R	Gas constant
T	Air temperature
t	Drying time

MATERIALS AND METHODS

Sample preparation:

Lemon fruits 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±1^{o}C) one hour before starting the experiments. For all experiments, lemons were washed and then cut to slices with 5±1mm thickness. The initial moisture content of lemon was 525±2% dry basis (d. b.).

Infrared (IR) Dryer Setup:

An infrared dryer with controllable temperature and radiation systems was used for the infrared drying process. The infrared (IR) dryer used in this research is equipped with circular IR emitter, lamp of 220 volt and 250W (Philips). Around the emitters are wave guards, with the purpose of minimizing radiant heat loss and improving uniformity of heating. The drying tray is located at bellow to the emitter. Lemon samples were placed in a single layer on the drying tray and heated from one side. Surface temperatures were measured with a Thermometer. Measurements were every 5 minutes for the first one hour and every 20 minutes until end of drying.

Experimental procedure:

Infrared drying process:

One layer of the lemon slices were 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± 0.1% % (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.

Mathematical modeling:

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

$$MR = \frac{M - M_e}{M_0 - M_e} \tag{1}$$

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 $M/\mathbf{M_0}$ 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):

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

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

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.

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

RESULTS AND DISCUSSIONS

Infrared drying:

As expected, increasing temperature of infrared dryer reduced the drying time (Fig. 1). At higher temperature, due to the quick removal of moisture, the drying process occurred in a shorter period. The decrease in drying time with increase in drying temperature may be due to increase in water vapor pressure within the lemon samples, which increased the migration of moisture, especially when the drying occurs only in falling rate period. Similar observation was reported for apple purees (Vergara*et al.*, 1997). 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 lemon samples 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. This matter indicates that diffusion is the controlling physical mechanism regulating moisture transfer in the sample slices. The similar results were reported by Kaymak-Ertekin (2002) for green and red peppers, Sogi*et al.*, (2003) for tomato seeds and Doymaz (2007) for pumpkin.

Figure 1 shows the effect of drying temperature and drying time on moisture ratio of lemon slices. As it can be seen in Fig.1, there is significant difference between four drying temperatures. Drying time has been reduced approximately to one third by increasing of temperature from 100 ^{o}C to 175 ^{o}C.

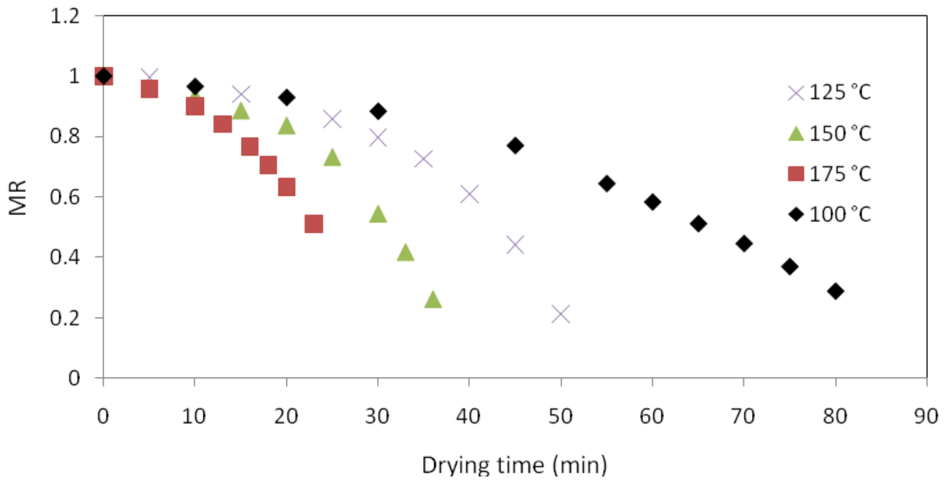

Fig. 1: Effect of drying temperature and drying time on moisture ratio of lemon slices.

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 2 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 lemon slices. Yousefi*et al.*, (2012) reported that two-term model was the best mathematical model to describe thin-layer hot air dryingof 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 *Cuminum cyminum* (R^2=0.994, RMSE=0.0225).

Table 2: Statistical results obtained from the selected models.

RMSE	R^2	Temperature (ºC)	Model
0.0610	0.9148	100	Newton
0.1358	0.7703	125	
0.1310	0.7900	150	
0.0629	0.8817	175	
0.0146	0.9945	100	Page
0.0371	0.9793	125	
0.0328	0.9850	150	
0.0119	0.9950	175	
0.0610	0.9148	100	Modified Page
0.1359	0.7703	125	
0.1310	0.7900	150	
0.0629	0.8817	175	
0.7451	0.9088	100	Henderson and Pabis
0.1255	0.7548	125	
0.1197	0.7712	150	
0.0557	0.8737	175	
0.0503	0.9088	100	Two- term
0.1245	0.7601	125	
0.0707	0.9207	150	
0.418	0.9289	175	
0.0413	0.9437	100	Logarithmic
0.1016	0.8378	125	
0.0916	0.8639	150	
0.0450	0.9172	175	
0.0086	0.9977	100	Wang and Singh
0.0310	0.9854	125	
0.0270	0.9885	150	
0.0066	0.9983	175	
0.0286	0.9746	100	Midilli *et al.*
0.1078	0.8307	125	
0.1094	0.8196	150	
0.0273	0.9696	175	

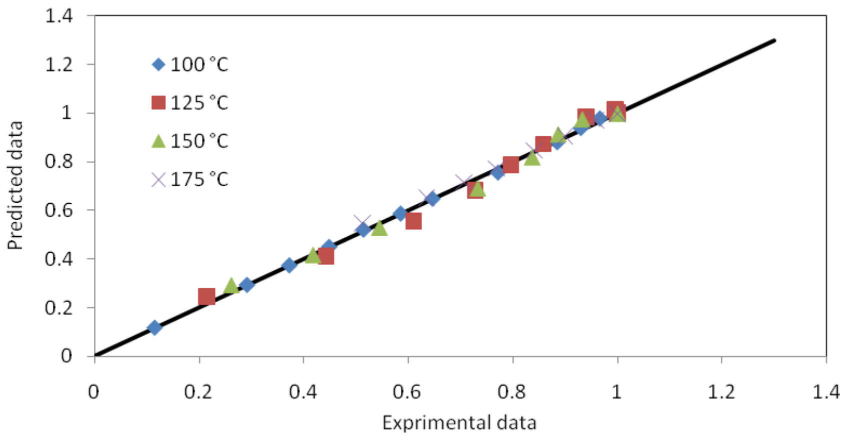

Fig. 2: Comparison of the experimental and predicted MR from Wang and Sing model.

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:

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

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:

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

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

The calculated D_{eff} values for different drying temperatures are shown in Fig. 3. D_{eff} value for lemon slices increased with temperature. This value for lemon slices was within the range of 9.9×10^{-10} to $2.76\times10^{-9} m^2/s$ over 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).

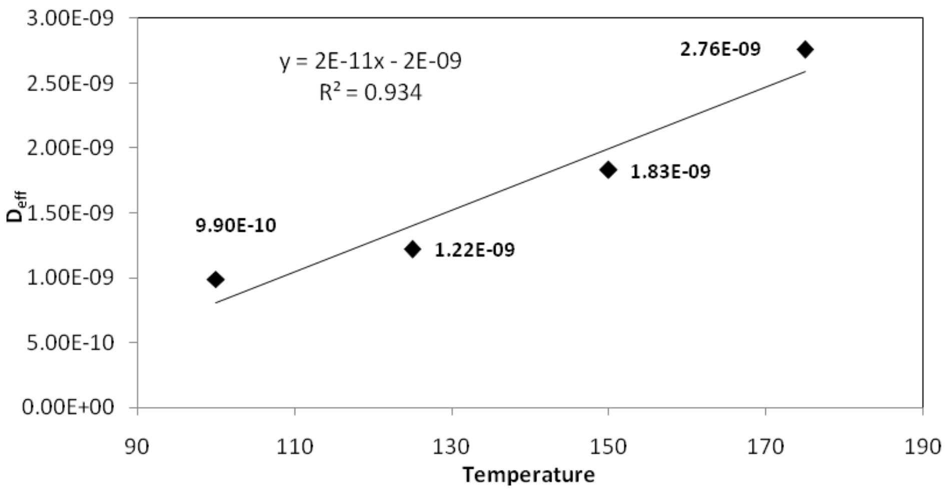

Fig. 3: Effect of drying temperature on the effective moisture diffusivity in lemon slices.

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 (Afzaland Abe, 1998). 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.

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:

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

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. 4).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).

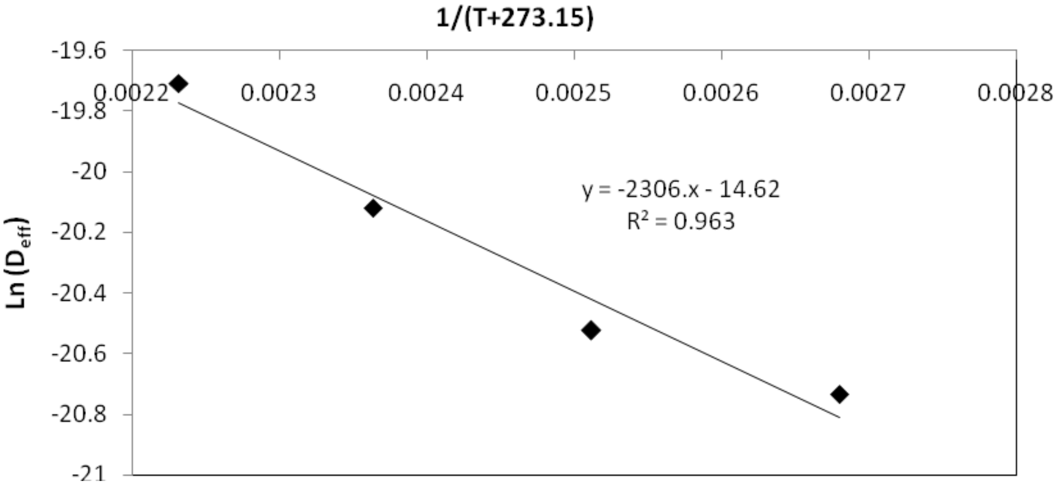

Fig.4: Arrhenius-type equation: Influence of drying temperature on the effective moisture diffusivity.

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. High value of R^2 in addition with low value for RMSE obtained for Wang and Singh mathematical model indicated the high performance of this model to determine MR during the drying process at all the drying temperatures. The obtained effective diffusivity was within the range of 9.9×10^{-10} to 2.76×10^{-9} m^2/s over the temperature range (100 to 175 ºC). It was found that, effective diffusivity increased with increasing drying temperature. The activation energy for lemon slices was found to be 87.61 kJ/mol using Arrhenius-type equation.

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