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A NEW APPROACH FOR MODELING OF HOT AIR-MICROWAVE THIN LAYER DRYING OF SOYBEAN

Mohsen Ranjbaran, Dariush Zare

Agricultural Engineering Department, Shiraz University, Shiraz, Iran

ABSTRACT

The drying characteristics of soybean during combined hot air-microwave drying were examined. The experiments were carried out for combination of five microwave power densities (0.89, 1.6, 3.2, 4.3, 5.3 W/g) and four levels of air temperatures (30, 40, 50 and 60 °C). Among several models which were fitted to the experimental data, the Modified Two Term model was introduced to be the most appropriate model to predict moisture ratio as a function of air temperature and microwave power density. The effective moisture diffusivity was calculated in the range from 8.740×10^{-10} m^2/s to 3.9664×10^{-9} m^2/s.

Keywords: hot air-microwave drying; effective moisture diffusivity; thin layer drying; soybeans.

NOMENCLATURE

C	Specific heat capacity, J/kg °C
D_{eff}	Effective moisture diffusivity, m^2/s
h_{fg}	Heat of vaporization of water, kJ/kg
M	Grain moisture content, kg/kg
m	Mass, kg
MBE	Mean bias error
MR	Moisture ratio
P_0	Microwave power density on the surface of material, W/g

p_0	Incident microwave power at the surface of material, W
R	Radius of a kernel, m
r	Radius, m
RH	Relative humidity of air, decimal, Pa/Pa
$RMSE$	Root mean square error
T	Temperature, ˚C
t	Time, s
v	Volume, m^3

Greek Letter

ρ	Density, kg/m^3
χ^2	Chi-square

Subscripts

0	Initial value
e	Equilibrium
exp	Experimental
pre	Predicted
w	Water

INTRODUCTION

Soybean is one of the most important sources of human and animal nutrition. In food industry, soybean is widely used to produce fat products such as refined edible soybean oil. Soybean can be harvested at the moisture content of about 18% (w.b) but for safe storage the harvested grains should be dried to less than 14% moisture content. Soybeans are brittle and may be damaged by too hot air due to moisture stress. For commercial consumption the maximum drying air temperature should be limited to 60 °C.

Microwave heating is used in many processes such as baking, pre-cooking and drying in industry. Microwaves cover a range of frequencies from 300 MHz to 30 GHz and the wavelength from 1 mm to 1 m [19]. The typical frequency used in microwave ovens is 2450 MHz. The microwave energy is absorbed by food materials and is converted into heat due to two mechanisms: the ionic interaction and the dipolar rotation. Salt and water are common molecules in most foods. Salt molecules are vibrated due to ionic interaction. On the other hand, the vibrations of water molecules are due to the dipolar rotation [24]. The wavelength of microwaves in a domestic microwave oven is 12.24 cm which is much greater than the diameter of a single kernel of soybean. Therefore, it can be assumed that the generation of energy in a soybean kernel is uniform. As a result, the coefficient of diffusivity of moisture for soybeans during microwave heating can be considered as a constant value.

Several researchers have worked on the conventional hot air drying of food materials such as rough rice [9], green beans [7.24], soybeans [11,12] and canola [32]. All studies show that the application of the conventional drying methods consumes long drying time and high amount of energy. Application of microwave heating in conjunction with the hot air drying would lead to a great reduction in drying time. Several studies have been performed in this way from which the works of Prabhanjan et al. [20] on carrot, Ren and Chen [23] on ginseng roots, Funebo and Ohlsson [8] on apples and mushrooms, McMinn [16] on lactose powder and Wang et al. [29] on apple, are of interest. Sharma and Prasad [26] studied on the drying of garlic cloves with hot air and combined microwave–hot air methods. The combined microwave-hot air drying were carried out at the air temperatures of 40, 50, 60 and 70 °C, and air velocities of 1.0 and 2.0 m/s by the use of microwave power of 40 W. The combined microwave-hot air drying caused a significant reduction in drying time of about 80-90 % in comparison with the conventional drying. Kouchakzadeh and Shafeei [13] have recently investigated the drying of two varieties of Iranian pistachio under microwave-convective treatment. Drying curves were fitted with seven moisture ratio models. They observed that the Page model [2] represented the best agreement with the experimental data according to the R^2 and χ^2 of curves fitting. The experiments were carried out in less than 30 min during hot air-microwave drying of pistachios. Applying microwave power for drying of food materials can increase their final quality [26,28]. Furthermore, studies indicate that microwave drying of grains before grinding helps reduce power consumption which is important in milling industries [28].

Conventional drying of soybeans consumes a large amount of energy and time. By adding microwave heating which leads to uniform generation of heat through the volume of each grain, the drying time decreases significantly and the air temperature can be applied to a lower degree. This can be seen in the operation of the microwave-assisted fluidized bed dryers. For mathematical modeling of such dryers, one needs to be aware of the kinetics of hot air-microwave drying of a single kernel which plays the role of an element for bulk grains. A thin layer drying equation can be considered as a single kernel drying equation in predicting the moisture content at any time of drying [3]. So, from the mathematical point of view, there is a need to find the thin layer drying equation undergoing hot air-microwave treatment for agricultural grains and seeds. Several studies have been done on hot air-microwave thin layer drying of food materials. In the most cases the moisture content of food material was predicted according to the microwave power of magnetron (W). Though such models may be precise, they cannot be used for future modeling of bulk drying of food materials such as fluidized beds. During hot air-microwave drying of bulk food materials the microwave power density (W/g) attenuates as the microwaves penetrate inside the material but the magnetron power would not change. On the other hand, all the microwave output power of magnetron would not be received by food and it is affected by the place of magnetron with respect to the food material. Therefore it seems that it is more reasonable to consider the microwave power density at the surface of food material. In the present study, as a new approach, the thin layer drying equations were determined according to the air temperature as well as microwave power density at the surface of grains (W/g). This feature can enhance the applicability of the model to be used for future modeling of microwave-assisted fluidized bed drying of grains [22,31]. As far as we know there is no information about hot air-microwave thin layer drying of soybean.

Therefore, the aims of this study are as:

- To study the effect of the air temperature and microwave power on the drying kinetics of soybeans.
- Determination of a thin layer drying equation for soybeans undergoing hot air-microwave drying.
- Determination of the effective moisture diffusivity for several drying conditions.

MATERIALS AND METHODS

Fresh soybean was purchased from a farm near Shiraz and used for the study without any pretreatment. Before the drying experiments, samples were stored at 3-4 °C in a refrigerator for about 72 hr for equilibration of moisture content. The initial moisture content of soybean kernels determined by standard oven drying method at 105 °C for 24 hr and it was in the range of 20 % to 21 % (d.b).

The average diameter of soybean kernels was measured as 5.42 mm by a micrometer. During all tests, the thickness of the bed was equal to a single soybean kernel diameter.

The drying experiments were carried out using a combined hot air-microwave dryer. The schematic of the apparatus is illustrated in Fig 1. The dryer consists of a domestic microwave oven (CC-4284TCR, LG, Korea) which has the capability of producing five different output powers including 180, 360, 540, 720 and 900 W, with the frequency of 2450 MHz and wavelength of 12.24 cm.

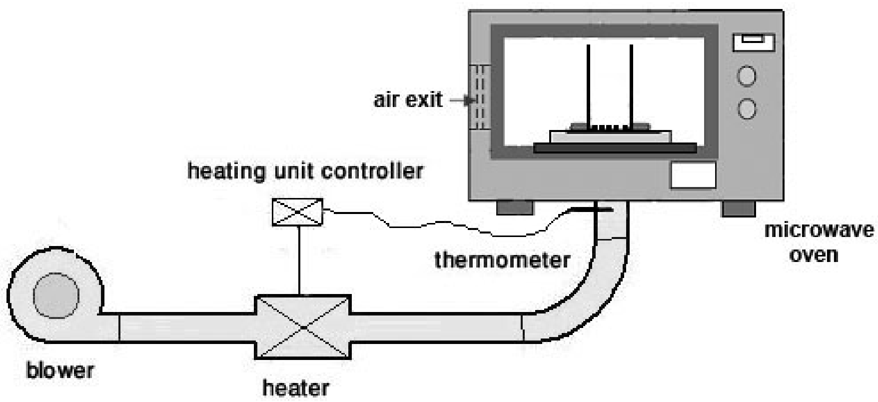

Fig 1. The schematic of the apparatus

The air conditioning part of apparatus consists of a variable speed fan controlled by an inverter (N50-007SF, Korea), two electrical pre-heaters of 1 kW as well as three of 0.5 kW. A temperature controller (SU-105IP, Samwon Engineering, Korea) was applied to keep the drying air temperature at a constant pre-defined value.

In order to deliver hot air to the sample, an opening of 10 cm diameter was made in the center and bottom of the microwave oven. The drying bed was a cylindrical Pyrex column of 60 mm diameter and 25 cm height. To ensure the uniformity of the intake air, the bed was equipped with a tephlon plate as an air distributor which was completely perforated by a number of 2 mm diameter circular holes. The air velocity approaching the bed tried to be kept constant at 0.4±0.05 m/s during all experiments, using Testo 425 (Germany) hotwire anemometer with accuracy of ±0.03 m/s.

Drying experiments were performed at five levels of microwave power (180, 360, 540, 720 and 900 W) and four levels of inlet air temperature (30, 40, 50 and 60 °C). The temperature and the relative humidity of drying air were measured using Testo 625 (Germany) with an accuracy of ±0.5 °C and ±2.5% RH. Then the absolute humidity of drying air was obtained from a psychrometric chart and it was in the range of 0.005-0.007 kg/kg for all experiments. During each drying experiment, a monolayer of soybeans of about 7±0.5 g was placed on the drying bed. The moisture loss was periodically measured by taking out the cylindrical Pyrex column and weighing on the digital balance (GF–600, A&D Company, Japan) having the accuracy of ±0.001 g. For each drying condition, three replications were performed. During all experiments weighing of drying samples was carried out in less than 10 s.

Modeling of the Moisture Ratio

To describe the moisture ratio as a function of drying time, eight different empirical and semi-empirical drying models were considered. These models which were also attempted by other researchers are presented in table 1. The reader ought to know that the time is in minutes in the given models.

The moisture ratio was calculated as follow:

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

where MR, M_0, $M(t)$ and M_e are the moisture ratio, initial moisture content (kg/kg), the moisture content (kg/kg) at a specific time and the equilibrium moisture content (kg/kg), respectively. The equilibrium moisture content of grain is defined as the moisture content at which the internal grain vapor pressure is in equilibrium with the vapor pressure of the environment [3].

In the present study the equilibrium moisture content was estimated using Henderson and Perry relationship for soybeans [18]:\

$$1 - RH = \exp(-0.000032\ (492 + 1.8\,T)M_e^{1.52}) \tag{2}$$

where RH is the relative humidity of air.

Determination of the Effective Moisture Diffusivity

Drying is a simultaneous heat and mass transfer process. The thermal energy required to evaporate moisture from the surface of a grain is provided by an external heat source, usually hot air. In addition, during microwave drying, heat is generated through the volume of grain kernels and leads to higher drying rate.

It has been reported that the moisture transfer from the interior to the surface of a kernel is occurred by diffusion. Several researchers have considered the diffusion as a dominant moisture transfer process during hot air microwave drying of food materials [1,19]. The mathematical model employed in this study is based on Fick's law of diffusion [3,6,7]:

$$\frac{\partial M}{\partial t} = \nabla^2(D_{eff}M) \tag{3}$$

where M is the moisture content of grain (kg/kg), t is time (s) and D_{eff} is the effective moisture diffusivity (m^2/s). Using spherical coordinates, for a constant value of D_{eff} the Eq. (3) can be written as:

$$\frac{\partial M}{\partial t} = \left(D_{eff}\ \frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\ \frac{\partial M}{\partial r}\right) \tag{4}$$

where r is the radius of a spherical kernel (m).

The following initials and boundary conditions are usually applied to solve the Eq. (4):

$$M(r,0) = M_0 \quad for \quad r < R \tag{5}$$

$$M(r_0,t) = M_e \quad for \quad t > 0 \tag{6}$$

The analytical solution of Eq. (4) for a spherical grain kernel with the assumptions of negligible shrinkage, moisture migration being by diffusion, constant temperature and diffusion coefficient [5] as well as constant microwave power density at the surface of grain kernel is as:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(\frac{-D_{eff}\,n^2\,\pi^2}{r^2}\ t\right) \tag{7}$$

The Eq. (7) can be simplified to the first term of the series solution. It has been reported by several researchers that this simplification does not have a great influence on the accuracy of prediction [6]:

$$MR = \frac{6}{\pi^2} \exp\left(\frac{-D_{eff}\,\pi^2}{r^2}\ t\right) \tag{8}$$

The Eq. (8) can be written in a linearized form:

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \frac{D_{eff}\,\pi^2}{r^2}\ t \tag{9}$$

This method has been demonstrated by several researchers [19,29]. Using Eq. (9), one can estimate the effective moisture diffusivity by plotting the experimental data in terms of ln (MR), versus time.

Estimation of the Microwave Power Density

The microwave power density at the surface of grains was determined experimentally using calorimetric method [1,30]. Five levels of microwave power were used to heat the distilled water existing in a Pyrex column. The Pyrex column was placed in three elevations in the center of the microwave oven for each power level. For each condition three different mass of distilled water was used. After the microwave heating, the averaged temperature rise ΔT_{ave} was determined after mixing the water sample to ensure uniform temperature distribution, using a thermometer. The mass of evaporated water, Δm, was measured to consider the energy used for evaporation. Therefore, the mass of distilled water was measured before and after microwave heating. The absorbed microwave power (W) was calculated for each test as follows:

$$p_0 = \frac{\rho_w v_w C_w \Delta T_{abs} + h_{fg} \Delta m}{t} \tag{15}$$

To evaluate the microwave power density P_0 (W/g) each calculated power was divided by the mass of distilled water. The data obtained for each power level was close to each other. An average value of P_0 was determined for each power level. The microwave power densities were calculated to be 0.89, 1.6, 3.2, 4.3 and 5.3 W/g.

Statistical Modeling Procedure

The non-linear regression analysis was performed using SPSS 15.0 software to determine the constants of the model. Eight general models existing in table 1 were fitted to the experimental data. The adequacy of fitness was determined by considering the coefficient of determination R^2, Chi-squareχ^2, Mean bias error (MBE) and Root mean square error ($RMSE$). The most appropriate model for MR was selected based on the highest value of R^2 and the lowest values for χ^2, MBE and RMSE [32].

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp} - MR_{pre}\right)^2}{N - z} \tag{16}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp} - MR_{pre}\right) \tag{17}$$

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp} - MR_{pre}\right)^2\right)^{0.5} \tag{18}$$

where MR_{pre} is the predicted moisture ratio, MR_{exp} is the experimental moisture ratio, N is the number of observations and z is number constants in the drying model.

Table 1. Mathematical models applied to drying curves.

No.	**Model Name**	**Model Eq.**	**References**
1.	Newton	$MR = \exp(-kt)$	[10]
2.	Page	$MR = \exp(-kt^n)$	[10]
3.	Henderson & Pabis	$MR = a\exp(-kt)$	[4]
4.	Logarithmic	$MR = a\exp(-kt) + c$	[10]
5.	Two term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	[10]
6.	Modified Two term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t) + c$	Present Study
7.	Verma *et al.*	$MR = a\exp(-kt) + (1 - a)\exp(-gt)$	[26]
8.	Midilli *et al.*	$MR = a\exp(-kt^n) + bt$	[17]

RESULTS AND DISCUSSION

Mathematical Modeling of Thin Layer Drying of Soybeans

Curve fitting has been performed on the eight previously mentioned drying models to correlate the moisture ratio with the drying time and the experimental conditions including air temperature and microwave power density.

The corresponding constants as well as the values of R^2, χ^2, MBE and $RMSE$ are given in table 2. The values of these coefficients indicate that all models were capable of predicting the kinetics of drying of soybeans very well. However, among those models examined, the Modified Two Term model was the most appropriate one with the values of 98.6 %, 0.00070, 0.00025 and 0.02610 for R^2, χ^2, MBE and $RMSE$, respectively. The experimental data of moisture ratio versus those predicted by Modified Two Term model is shown in Fig 2 which indicates the suitability of the mentioned model.

Table 2. Statistical results of mathematical modeling of drying curve

No.	Model Name	Model Constants	R^2 (%)	χ^2	MBE	$RMSE$
1.	Newton	$k = 0.002\,T + 0.042\,P_0 - 0.042$	97.0	0.00146	0.00363	0.03813
2.	Page	$k = 0.002\,T + 0.047\,P_0 - 0.005$ $n = 0.004\,T + 0.003\,P_0 + 0.683$	97.9	0.00105	0.00134	0.03217
3.	Henderson & Pebis	$a = 0.000012\,T - 0.001P_0 + 0.975$ $k = 0.002\,T + 0.041\,P_0 - 0.046$	97.3	0.00133	0.00085	0.03634
4.	Logarithmic	$a = 0.004\,T + 0.022\,P_0 + 0.536$ $k = 0.002\,T + 0.063\,P_0 - 0.022$ $c = -0.004\,T - 0.015\,P_0 + 0.418$	98.0	0.00099	0.00008	0.03122
5.	Two term	$a = 0.015\,T - 0.021\,P_0 + 0.062$ $k_0 = 0.0000707\,T + 0.069\,P_0 + 0.101$ $b = -0.014\,T + 0.025\,P_0 + 0.904$ $k_1 = -0.003\,T + 0.034\,P_0 + 0.070$	98.3	0.00085	0.00020	0.02883
6.	Modified Two term	$a = -0.014\,T + 0.202\,P_0 + 0.457$ $k_0 = -0.007\,T + 0.076\,P_0 + 0.248$ $b = 0.021\,T - 0.145\,P_0 - 0.166$ $k_1 = -0.002\,T + 0.159\,P_0 + 0.079$ $c = -0.006\,T - 0.050\,P_0 + 0.665$	98.6	0.00070	0.00025	0.02610
7.	Verma *et al.*	$a = 0.010\,T + 0.044\,P_0 - 0.296$ $k = 0.008\,T + 0.043\,P_0 - 0.442$ $g = 0.004\,T + 0.066\,P_0 - 0.072$	98.1	0.00090	0.00043	0.02978
8.	Midilli *et al.*	$a = -0.001\,T + 0.008\,P_0 + 1.017$ $k = 0.001\,T + 0.005\,P_0 + 0.016$ $n = 0.004\,T - 0.006\,P_0 + 0.720$ $b = 0.011$	97.9	0.00102	0.00027	0.03155

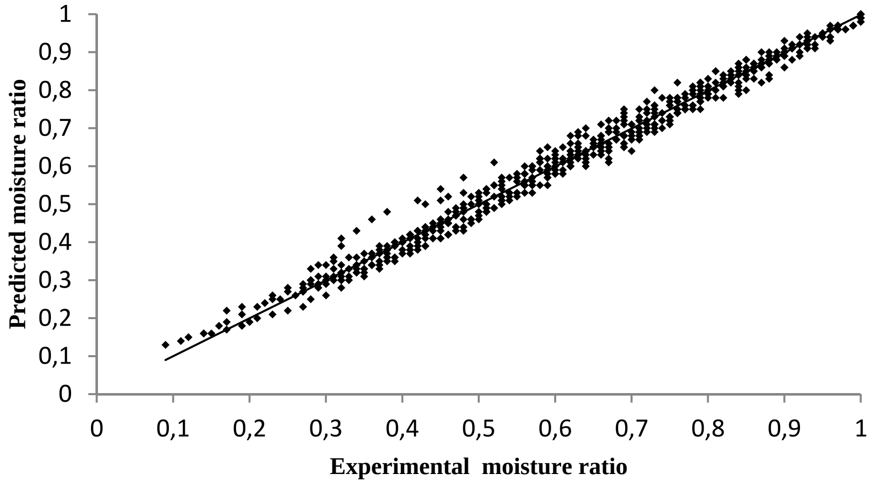

Fig 2. The experimental data versus predicted data of moisture ratio for the Modified Two Term model

The Effect of Microwave Power on the Drying Kinetics of Soybeans

Five different levels of microwave power densities including 0.89, 1.6, 3.2, 4.3 and 5.3 W/g were applied to determine the effect of microwave power on the drying kinetics of soybeans. The variation of the moisture ratio versus drying time for the experimental data and the Modified Two Term model, at the various microwave power densities for the drying air temperature of 40 °C is illustrated in Fig 3. It can be seen that as the microwave power density is increased, the slope of drying curves becomes sharper. The drying time is decreased significantly in comparison with hot air drying of soybeans [21] which reflects higher drying rates. Sharma and Prasad [26] have reported that the application of microwave power in conjunction with hot air heating would result in higher drying rates. The accelerated drying rate is due to internal heat generation within the food material when they are under the exposure of microwaves [14] which makes the internal vapor pressure in a grain kernel to rise rapidly. By progressing of drying time, the effect of microwave power on the drying of soybeans decreases due to reduction of grains moisture content. Such phenomenon has been observed by other researchers during hot air-microwave drying of food materials [13,26].

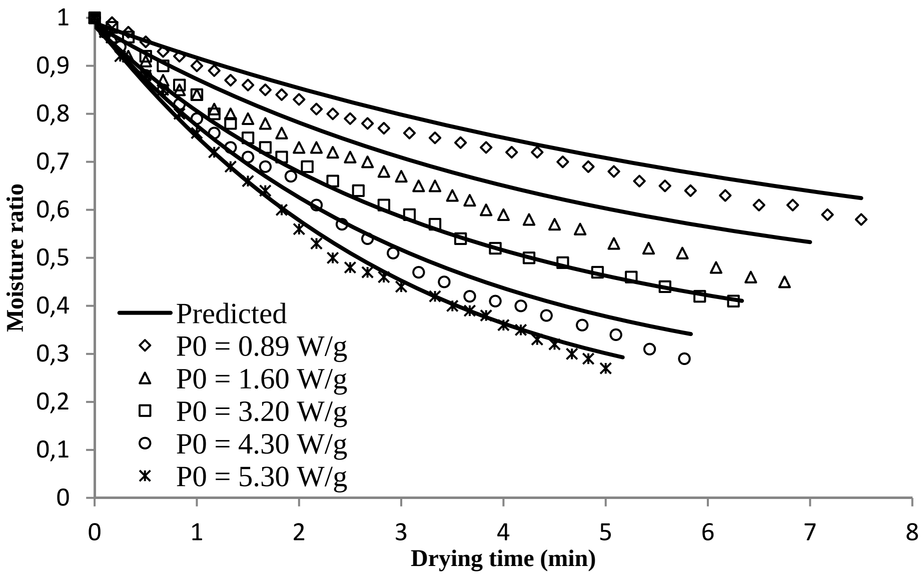

Fig 3. The variation of the moisture ratio versus drying time for the experimental data and the Modified Two Term model, at the various microwave power densities for the drying air temperature of 40 °C.

The Effect of Air Temperature on the Drying Kinetics of Soybeans

To investigate the effect of air temperature on the drying kinetics of soybeans four different levels of air temperature including 30, 40, 50 and 60 °C were used. Fig 4 shows the variation of moisture ratio versus drying time, for the experimental and predicted data at various air temperatures and microwave power density of 3.2 W/g. Comparing

Fig 3 and 4, it can be seen that the moisture removal is more closely linked with the level of microwave power than air temperature.

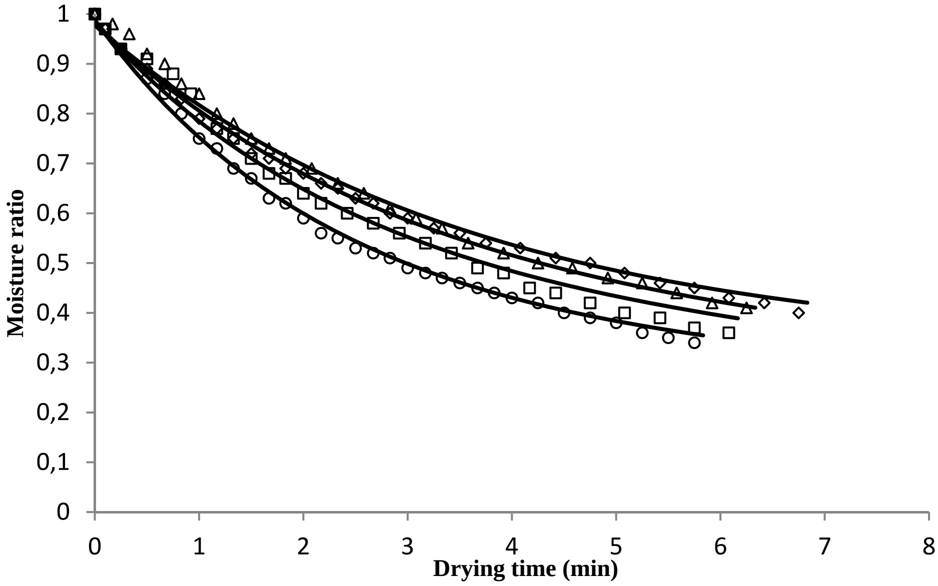

Fig 4. The variation of the moisture ratio versus drying time for the experimental data and the Modified Two Term model, at the various air temperatures for the microwave power density of 3.2 W/g; (—) predicted, (◊) 30 °C, (Δ) 40 °C, (□) 50 °C, (○) 60 °C.

Determination of the Effective Moisture Diffusivity

To estimate the effective moisture diffusivity for soybeans the natural logarithm of experimental moisture ratio,ln (MR), was calculated. The slopes of the plot of ln (MR) versus drying time were calculated to obtain the effective moisture diffusivity by the following equation:

$$slope = \frac{\pi^2 D_{eff}}{r^2} \tag{19}$$

where r is the averaged radius of a single soybean kernel (m).

The plot of ln (MR) versus drying time for different microwave powers and air temperature of 40 °C is illustrated in Fig 5. It can be seen that as the microwave power density increases the plot of ln (MR) becomes steeper which reflects higher moisture diffusivity through grains.

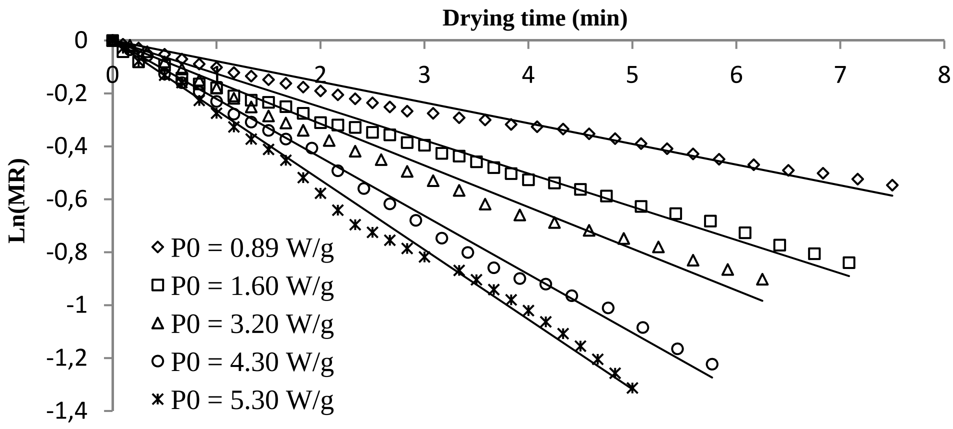

Fig 5. The variation of ln(MR) versus drying time for different microwave power densities and at air temperature of 40 °C

Furthermore, the plot of ln (MR) versus drying time for different air temperatures and at the constant microwave power density of 4.3 W/g is shown in Fig 6. By applying higher air temperature the diffusivity coefficient increases [7,15] and the drying time decreases. A comparison between these curves indicates that the effect of microwave power on the effective moisture diffusivity is more than air temperature.

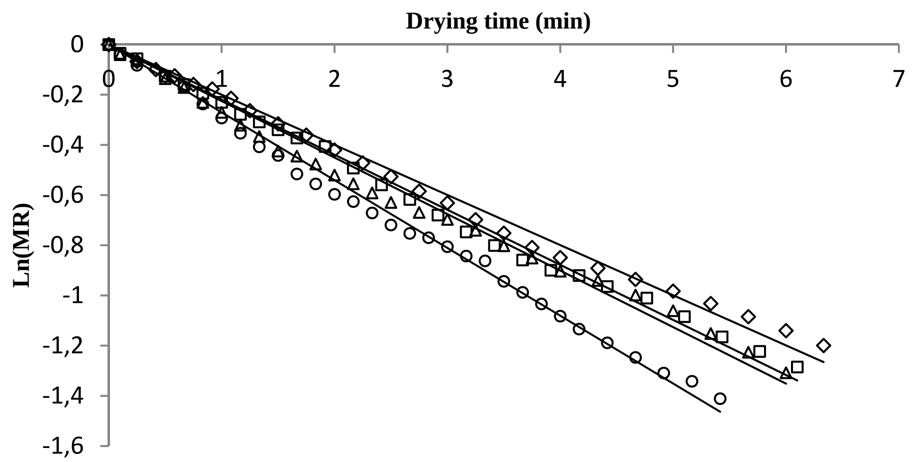

Fig 6. The variation of ln(MR) versus drying time for different air temperatures and at the microwave power density of 4.3 W/g; (─) predicted, (◊) 30 °C, (□) 40 °C, (Δ) 50 °C, (○) 60 °C.

The values of calculated effective moisture diffusivity for different microwave power densities and air temperatures are summarized in table 3. The values of R^2 reflect adequate fitting. It can be seen that the values of D_{eff} have increased proportional to the increase of microwave power density and air temperature. Madamba et al. [15] have reported that the values of D_{eff} for food materials are generally in the range of 10^{-11} to 10^{-9} m^2/s, during hot air drying. In the present study the D_{eff} was calculated from 8.740×10^{-10} m^2/s to 3.9664×10^{-9} m^2/s which is higher than the mentioned general range due to application of microwave power during drying.

Table 3. The calculated effective moisture diffusivity for different drying conditions.

T (°C)	P_0 (w/g)	Slope (1/min)	$D_{eff}\times10^9$ (m^2/s)	R^2 (%)
30	0.89	0.071	0.8740	98.1
40	0.89	0.078	0.9602	97.2
50	0.89	0.090	1.1080	99.0
60	0.89	0.123	1.5142	94.3
30	1.60	0.120	1.4773	97.6
40	1.60	0.125	1.5388	97.2
50	1.60	0.155	1.9081	96.7
60	1.60	0.184	2.2651	97.6
30	3.20	0.150	1.8466	93.1
40	3.20	0.157	1.9327	97.7
50	3.20	0.197	2.4252	99.3
60	3.20	0.218	2.6837	97.2
30	4.30	0.201	2.4744	99.2
40	4.30	0.219	2.6960	99.4
50	4.30	0.227	2.7945	97.8
60	4.30	0.271	3.3362	99.5
30	5.30	0.242	2.9792	97.6
40	5.30	0.263	3.2367	99.2
50	5.30	0.274	3.3731	97.9
60	5.30	0.322	3.9664	98.7

The following empirical equation was obtained to estimate effective moisture diffusivity as a function of drying constants of the Modified Two Term model (k_0 and k_1), air temperature (°C) and microwave power density (W/g). The relationships of drying constants of Modified Two Term model have been given in table 2.

$$D_{eff} \times 10^9 = a_0\, K_0^2 + a_1\, K_1^2 + a_2 \qquad (20)$$

where,

$$a_0 = -0.143\, T + 2.005\, P_0 + 23.215$$
$$a_1 = 0.194\, T + 1.634\, P_0 - 30.526$$
$$a_2 = 0.010\, T + 1.808\, P_0 - 0.665$$

The values of R^2 and χ^2 are 98.2 % and 2.6102×10^{-11}, respectively.

The relationship between the empirical and estimated values of effective moisture diffusivity is illustrated in Fig 7. It is shown that the Eq. (20) is capable of predicting the effective moisture diffusivity reasonably.

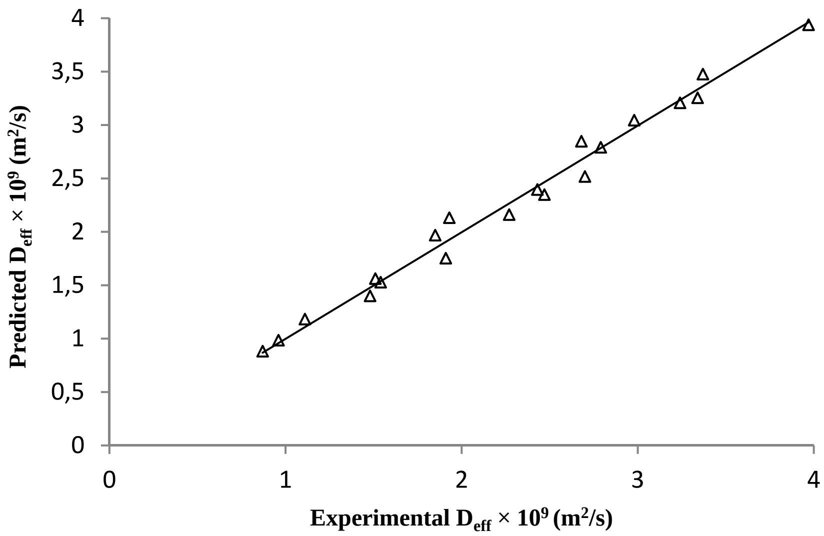

Fig 7. The experimental data versus predicted data of the effective moisture diffusivity

CONCLUSIONS

The drying characteristics of soybeans undergoing hot air-microwave heating were studied. Several empirical and semi-empirical models for predicting moisture ratio were fitted to the experimental data by the non-linear regression analysis using SPSS 15.0 software. The most appropriate model was the Modified Two Term model with the values of 98.6 %, 0.00070, 0.00025 and 0.02610 for R^2, χ^2, MBE and $RMSE$, respectively. Applying microwave power in conjunction with hot air drying led to higher drying rates in comparison with the conventional hot air drying. The effective moisture diffusivity for several drying conditions was calculated in the range from 8.740×10^{-10} m^2/s to 3.9664×10^{-9} m^2/s.

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Mohsen Ranjbaran
Agricultural Engineering Department, Shiraz University, Shiraz, Iran
agricmachinary@yahoo.com

Dariush Zare (Corresponding Author)
Agricultural Engineering Department, Shiraz University, Shiraz, Iran
Tel.: +98 711 6138192 ; Fax: +98 711 2286104
Email addresses: dzare@shirazu.ac.ir

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