Prediction of Dehydration Characteristics of Tarom Garlic slices in Microwave-convection Combination

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a, b	**coefficients in models**
A_0, A_1, A_2	**regression coefficients**
A,B,C,D	**constants of regression**
D_{eff}	**effective diffusivity, $m^2\ s^{-1}$**
$(D_{eff})_{Avg}$	**average effective moisture diffusivity, $m^2\ s^{-1}$**
D_0	**pre-exponential factor, $m^2\ s^{-1}$**
E_a	**activation energy, kJ mol^{-1}**
F_0	**fourier number**
k, k_0	**dehydration rate constants in models, min^{-1}**
M	**moisture content at any time, %d.b.**
M_e	**equilibrium moisture content, %d.b.**
M_0	**initial moisture content, %d.b.**
M_l	**local moisture content, %d.b.**
$M_{R,ex}$	**experimental dimensionless moisture ratio**
$M_{R,pre}$	**predicted dimensionless moisture ratio**
m	**exponent in drying model**
N	**number of observations**
n	**positive integer**
r	**the radius of the cylinder, m**
R	**universal gas constant, kJ $mol^{-1}\ K^{-1}$**
R^2	**coefficient of determination**
t	**drying time, s**
T	**absolute air temperature, K**
l_n	**the nth root of the Bessel function of zero order**
∇	**operator**

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Abstract

The convection and microwave-convection drying of garlic cloves were carried out in a laboratory scale microwave dryer, which was developed for this study. On both techniques the sample sizes were about 1.09 gr each, and with thicknesses of 5 and 7 mm. Experiments were carried out at temperature of 40 ° C, 100 ° C and 140 ° C at air velocity of 1.0 m/s in microwave-convection method using powers of 100, 180 and 300 W. The effect of air temperature and sample thickness and in microwave-convection the effect of power, on dehydration characteristics of garlic slices was examined. The transport of water during dehydration was described by Fick's equation and the effective diffusivity was between 2.9 and 31 $\times 10^{10}\ m^2/s$ in microwave-convection method and, between 0.7 and 5.6 $\times 10^{10}\ m^2/s$ in convection method. The effect of temperature on the effective diffusivity was described by the Arrhenius-type relationship. The activation energy in the microwave-convective drying ranged between 2.54 and 14.67 kJ/mol and in convective drying was between 16.38 and 18.84 kJ/mol .On both methods, the experimental dehydration data of garlic slices were fitted to the five well-known semi-theoretical drying models, i.e. the Henderson and Pabis, two term, Lewis, page and verma et al.models. The accuracies of the models were measured using the coefficient of determination(R^2), root mean square error (RMSE) and sum of square error (SSE). All five models are acceptable for describing dehydration characteristics of garlic slices, however based on statistical analysis, the page, the verma and the two-term model showed a better performance to predict dehydration characteristics.

In this paper, after examining above mentioned models, a mathematical model was developed and showed better fitness to the experimental data compared to the other models.

Keywords: drying – microwave - convection –garlic- diffusivity - modeling

1-Introduction

Garlic is an important crop for medicinal and culinary purposes. It is mainly used as a condiment in various food preparations such salad dressing, stews, spaghetti, pickles, etc. Garlic is of a great economic importance in Tarom, situated in Guilan province, north of Iran and is produced with a high quality[1].

Moisture content is one of the most important factors affecting the quality of garlic during prolonged storage. Dehydration operations are important steps in the chemical and food processing industries. The basic objective in drying food products is the removal of water in the solids up to a certain level, at which microbial spoilage and deterioration chemical reactions are greatly minimized[7].

Microwave drying has several advantages over conventional hot air drying, such as higher drying rate, minimal heating at locations with less water thus reducing overheating of locations where heating is not required. Microwave has been used as a heat source since the 1940s (Mermelstein, 1997). This technique has been extensively employed in the food and chemical engineering industries. The food industry is the largest consumer of microwave energy, where it can be employed for cooking, drying, freeze-drying, sterilization, baking (Ayappa et al., 1991a).

Microwave energy penetrates into a food material and produces a volumetrically distributed heat source, due to molecular friction resulting from dipolar rotation of polar solvents and from the conductive migration of dissolved ions. The dipolar rotation is caused by variations of the electrical and magnetic fields in the product (Alton, 1998). Water, the major constituent of most food products, is main source for microwave interactions due to its dipolar nature [8]. Heat is generated throughout the material, leading to faster heating rates and shorter processing times compared to convectional heating, where heat is usually transferred from the surface to the interior. The diffusion coefficient of a food is a material property which its value depends upon the conditions of the material. Effective moisture diffusivity describes all possible mechanisms of moisture movement within the foods, such as liquid diffusion, vapour diffusion, surface diffusion, capillary flow and hydrodynamic flow (Kim & Bhowmik, 1995). A knowledge of effective moisture diffusivity is necessary for designing and modeling mass-transfer processes such as dehydration, adsorption and desorption of moisture during storage [6]. Therefore the main objectives of this study are:

(1) To determine the effect of drying air temperature, slice thickness, and beside in microwave-convection, the effect of microwave power, on the dehydration characteristics of Tarom garlic.
(2) To fit the obtained experimental dehydration data to semi-theoretical models this widely used to describe thin-layer drying of agricultural products.
(3) To introduce a new semi-theoretical model that can fit the experimental dehydration data better than other models which are used in the literature.
(4) Comparison between two different techniques that have been applied in this study.

2-Materials and method

The garlic bulbs were purchased from a local market of Guilan province in Iran, for this study. They were stored in a cold chamber maintained approximately at a temperature of $1^{\circ}C$ and about 80 % relative humidity. Medium size bulbs were manually cracked to separate cloves. Then, the cloves were hand peeled and cut into slice thicknesses of 5 and 7 mm with an error of ± 0.5mm. The sample lot consisted of cloves of uniform size, each clove weighing about 1.09 g. All of garlic samples used for dehydration were from the same batch. This experiment was replicated three times to obtain a reasonable average. After drying, the sample was found to have moisture content of 210% d.b. Dehydration equipments in both techniques were performed in a laboratory scale microwave-convective dryer. Temperatures of $40^{\circ}C$, $100^{\circ}C$ and $140^{\circ}C$ at air velocity of $1.0\,m/s$, and for microwave-convective drying, microwave power of 100,180, and 300W were applied.

The dryer was run idle for about 15 minutes to reach thermal stabilisation. After this period the samples were uniformly spread over the tray as a single layer and dehydrated there. In convective drying, the sample mass was recorded at 10 min intervals for first hour and 20 min subsequently there after but in the microwave-convective drying, weighing of sample was carried out every 5min during the drying process, under all drying conditions. Dehydration process was continued until no further changes in their mass were observed. But it’s good to notice that in both techniques the dehydrated slices were cooled for 15minutes in desiccator before weighing.

3-Theoretical considerations

The mechanism of mass transfer in foods is complex. The dehydration of biological materials normally follows a falling-rate drying period. The moisture and/or vapour migration during this period is controlled by diffusion. The method of slopes was used in the estimation of effective moisture diffusivity of garlic slices at corresponding moisture contents under different drying conditions. The garlic cloves were assumed as infinite cylinders, i.e. moisture diffusion occurring radially outwards only (crank,1975)[3]. Following assumptions were made for the infinite cylindrical shaped body of the garlic clove. Assuming that the resistance to moisture migration in uniformly distributed throughout the mass of a sample, Fick's second law can be derived as follows:

$$\frac{\partial M_l}{\partial t} = \nabla(D_{eff} \nabla M_l) \qquad (1)$$

Where: M_l is the local moisture in %d .b; t is the drying time in min; and D_{eff} is the effective diffusivity in m^2/s.

Assuming that the moisture is initially uniformly distributed throughout the sample, mass transfer is symmetric with respect to the center, that the surface moisture content of the sample instantaneously reaches equilibrium with the conditions of the surrounding air, shrinkage is negligible or not taken into consideration, and resistance to mass transfer of the surface is negligible compared to internal resistance of the sample. The solution of Eq. (1) for an infinite cylinder can be defined as follows :

$$\frac{M_t - M_e}{M_0 - M_e} = MR = \sum_{n=1}^{\infty} \frac{4}{l_n^2} \exp\left(-\frac{l_n^2 D_{eff} t}{r^2}\right) \qquad (2)$$

Where: MR is the moisture ratio, dimensionless; M $_0$, the moisture content at time t = 0 , g water / g dry matter; M $_t$, the moisture content at time t, g water/ g dry matter; M $_e$, the equilibrium moisture content,g water/g dry matter; D $_{eff}$, the moisture diffusivity, m^2/s;r, the radius of the cylinder,m; t, drying time ,s; l_n is the nth root of the Bessel function of zero order, n=1,2,3,….

Eq. (2) is evaluated numerically for Fourier number, $F_0 = D_{eff} \cdot t/r^2$, for diffusion and thus can be re-written as :

$$MR = \frac{4}{l_1^2} \exp(-l_1^2 F_0)$$

For n=1 and l_1=2.405 (Eqn(1)), the above equation takes the following form,

$$F_0 = -0.173 \ln(MR) - 0.0637$$

Where $F_0 = D_{eff} \cdot t/r^2$, and

$$D_{eff} = \frac{(F_0)_{th}}{(t/r^2)_{\exp}} \qquad (3)$$

Thin-layer drying models that describe the drying behavior of biological materials fall into three categories, namely, theoretical, semi-theoretical and empirical. The semi-theoretical models are generally derived by simplifying general series solutions of Fick's second law or modification of simplified models and valid within the temperature, relative humidity, air flow rate and moisture content range for which they were developed. Among the thin-layer drying models, the Henderson and Pabis model (Henderson & Pabis , 1961), the two-term model (Henderson, 1974), the lewis model(Lewis, 1921) and the Page model (Page, 1949), the Verma et al.(Verma et al. , 1985)are used frequently. By using Eq. (2) the Henderson and Pabis model can be written as:

$$MR = a \exp(-kt) \qquad (4)$$

Where: a is the coefficient in drying model; k is the dehydration rate constant in min $^{-1}$; and t is the drying time in min.

The same as Henderson and Pabis model, the Two-term model can be derived by using Fick's equation regardless of particle geometry and boundary conditions. However, it requires constant product temperatures during drying process and assumes that diffusivity is constant. It is written in the form of:

$$MR = a \exp(-kt) + b \exp(-k_0 t) \qquad (5)$$

Where: b is the coefficient in drying model; and k $_0$ is the dehydration rate constant in min $^{-1}$.

The simple lumped model analogous to Newton's law cooling in heat transfer is often used to describe mass transfer in thin layer drying. The Lewis model is as below:

$$MR = \exp(-kt) \qquad (6)$$

This model has been used commonly by Ross and White (1972) for maize, White et al. (1981) for maize and Bruce (1985) for barley. However, it tends to overestimate the early stages and underestimate the later stages of the drying curves[2].

To overcome the shortcomings of the Lewis models, the Page model is applied with an empirical modification to the time term by introducing an exponent. It is written as follows:

$$MR = \exp(-kt^{m}) \qquad (7)$$

The Verma et al. model:

$$MR = a\exp(-kt) + (1-a)\exp(-bt) \qquad (8)$$

Where: a and b are the coefficient in drying model.

This model has been applied by Ekavak Akpinar (2005) for parsley, mint and basil, Y.Soysal and S.Oztekin and O.Eren (2006) for parsley[4].

In this paper , another model was developed which is:

$$MR = a\exp(-kt^{m}) + (1-a)\exp(-bt) \qquad (9)$$

This model shows a very good fitness to the experimental data. This model predicts the drying behaviour of garlic slices accurately.

3-1-Analysis of dehydration data

The obtained experimental dehydration data of garlic slices were fitted to the five well-known semi-theoretical drying models, i.e. the Henderson and Pabis, two-term, Lewis, Page, Verma models and the developed model. The dehydration rate constants of models were estimated using a non-linear regression procedure. Then adequacy of models was evaluated and compared by means of the coefficient of determination $(R)^{2}$, root mean square error analysis (RMSE) and sum of square error (SSE).

$$R^{2} = \frac{\sum_{i=1}^{N}(MR_{i} - MR_{pre,i}) \cdot \sum_{i=1}^{N}(MR_{i} - MR_{exo,i})}{\sqrt{[\sum_{i=1}^{N}(MR_{i} - MR_{pre,i})^{2}].[\sum_{i=1}^{N}(MR_{i} - MR_{\exp,i})^{2}]}} \qquad (10)$$

$$RSME = [\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{\exp,i})^{2}]^{1/2} \qquad (11)$$

$$SSE = \sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^{2} \qquad (12)$$

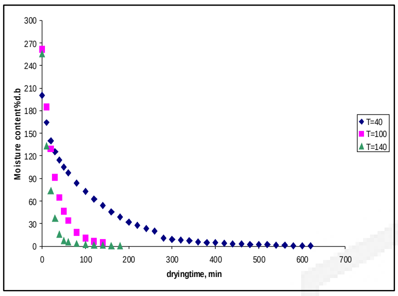
Where: $MR_{\exp,i}$ is the ith experimental dimensionless moisture ratio; $MR_{pre,i}$ is the ith predicted dimensionless moisture ration; and N is the number of observations. The coefficient of determination R^{2} was used as the primary comparison criteria for selecting the best model to fit the six models to the experimental data. The higher the values of the R^{2} and lowest values of the RMSE and SSE, the better the goodness of the fit. (Akpinar, Brice & Midilli, 2003; Akpinar, Brice & Yildiz, 2003; Akpinar et al., 2003; Midilli & Kucuk, 2003).

4-Results and discussion

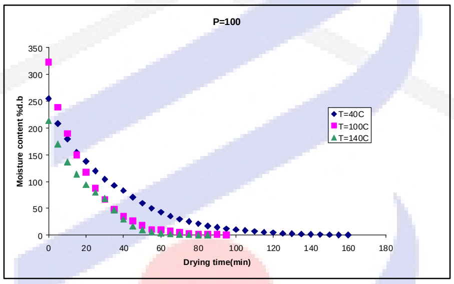
4-1-Dehaydration characteristics

Dehydration characteristics of garlic slices in convective drying at 40°C, 100°C and 140°C air temperature for a sample thickness of 5mm is presented in fig.(1). Also for microwave-convective drying in 100 W of microwave power and at 40°C, 100°C and 140°C air temperature for a sample thickness of 5mm is presented in fig.(2). As expected, the drying time decreased considerably with an increase in the air temperature. As indicated in these curves, there was no constant rate period in garlic drying process. It is apparent that moisture content decrease continuously with drying time. The similar trends were obtained for a sample thickness of 7mm in both methods. Figure3 shows the influence of sample thickness on dehydration characteristics of garlic slices at 100°C air temperature. Similar results were obtained at 40°C and 140°C air temperatures. Figure4 shows the influence of sample thickness on dehydration characteristics at 40 ° C air temperature and 100Wof microwave power. Similar results were obtained at 40 ° C and 140 ° C air temperatures and 180,300 W of microwave power. The increase in the sample thickness causes an increase in the drying time. This increase was due to the reducing distance the moisture travels and increasing surface area exposed for a given volume of the samples. Fig.(5) shows that using microwave power decreases the drying time in comparison with the convective drying, even in 7mm thickness sample.

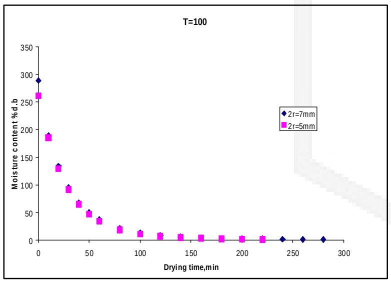
In both methods, most of dehydration of garlic slices took place in the falling rate drying period. An analysis of the falling rate period was carried out to understand the drying kinetics by determination of effective moisture diffusivity (D_{eff}), the influence of moisture content on the effective moisture diffusivity and the activation energy involved in various conditions of convective and microwave-convective drying.



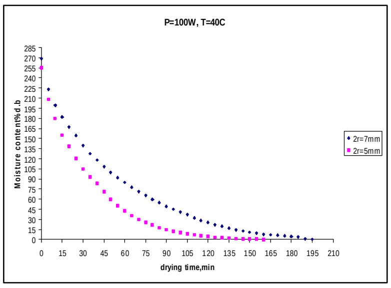
Fig(1)Influence of air temperature on the dehydration characteristics of garlic slices in convective drying, at sample thickness of 5mm, and various air temperatures: 40 ° C, 100 ° C and140 ° C.



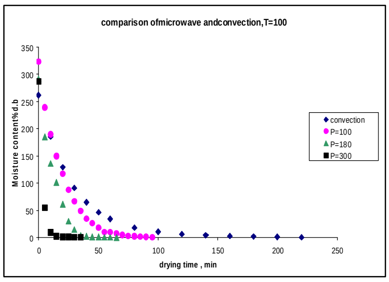
Fig(2) Dehydration characteristics of garlic slices in microwave-convective drying in 100 W of microwave power and at 40 ° C, 100 ° C and 140 ° C air temperature for a sample thickness of 5mm



Fig(3) Influence of sample thickness on the dehydration characteristics of garlic slices in convective drying, at 100 ° C air temperature and different sample thickness, 5 and 7 mm.



Fig(4) Influence of sample thickness on the dehydration characteristics of garlic slices in microwave-convective drying, in microwave power of 100 W and at 40 ° C air temperature and different sample thickness, 5 and 7 mm.



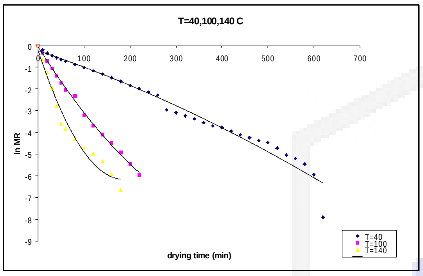
Fig(5) Influence of air temperature on the dehydration characteristics of garlic slices in microwave-convective and convective drying, at a sample thickness of 5mm and temperature of 100 ° C and various microwave powers: 100W, 180W and 300W.

4-2-Effective moisture diffusivity (D_{eff})

The logarithm of moisture ratio values (lnMR) were plotted against average drying time (t) for different drying conditions and the plots for microwave-convective and convective drying of garlic cloves is shown in fig.(6) and (7). It has been seen from the figures that the relationships were non-linear in nature under all the studied drying conditions. This non-linearity in the relationship may be due to the reasons like shrinkage in the product, non-uniform distribution of initial moisture, variation in moisture diffusivity with moisture content and change in product temperature during drying (Adu & Otten, 1996; Khraisheh, Cooper, &Magee, 1997)[3]. The non-linearity of the curves is an indicative of the variation in moisture diffusivity with moisture content. A second order polynomial relationship between lnMR and drying time t, was fitted well and related equation is given below:

$$\ln MR = A_0 + A_1 t + A_2 t^2 \qquad (13)$$

Regression coefficients A_0, A_1 and A_2 and the corresponding values of coefficients of determination (R^2) for convective and microwave-convective drying are presented in Table 1.



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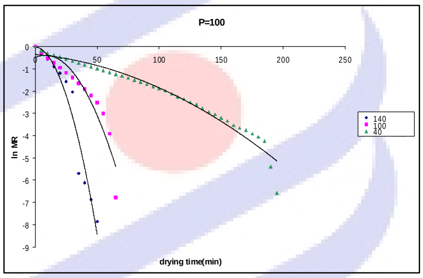
Fig(6) Plot of ln(MR) vs. drying time for garlic cloves at various air temperatures for the sample thickness of 5mm, in convective drying



Fig(7) Plot of ln(MR)vs drying time for garlic cloves at various air temperature for the sample thickness of 5mm, in microwave- convective drying.

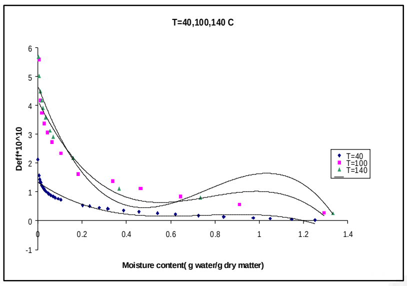
4-3- Effective of moisture content on effective moisture diffusivity

The variation in moisture diffusivity with moisture content is complex and system specific function. The effective moisture diffusivity (D_{eff}) of a food material characterizes its intrinsic moisture mass transport property and includes molecular diffusion, liquid diffusion, vapour diffusion, hydrodynamic flow and other possible mass transport mechanisms (Karathanos, Vill-alobos, & Saravacos, 1990)[3]. The effective moisture diffusivity (D_{eff}) was estimated by substituting the positive values of $(F_0)_{th}$ and the drying time t along with the average radius of the garlic clove (2.5 and 3.5mm) in Eq.(3),for each corresponding moisture content under different drying conditions.

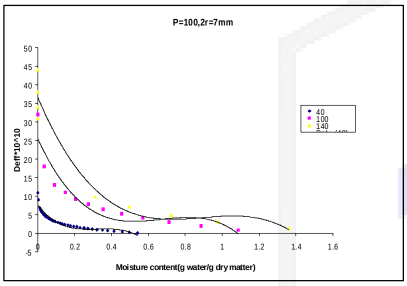
The values of D_{eff} corresponding to positive F_0 values were plotted against moisture content under all drying conditions and the variations are presented in figs.(8) and (9). The D_{eff} values increased with decrease in moisture content under all drying conditions. This may indicating that as moisture content decreased, the permeability to vapour increased, provided the pore structure remained open. The temperature of the product rises rapidly in the initial stages of drying due to more absorption of microwave heat, as the product has a high loss factor at high moisture content. This increases the water vapour pressure inside the pores and results in pressure induced opening of pores. In the first stage of drying, liquid diffusion of moisture could be the main mechanism of moisture transport. As drying progressed further, vapour diffusion could have been the dominant mode of moisture diffusion in the latter part of drying. A third order polynomial relationship was found to correlate the effective moisture diffusivity (D_{eff}) with corresponding moisture content (M) of garlic and is given by Eq. (14)

$$D_{eff} = A + BM + CM^2 + DM^3 \qquad (14)$$

Where: D_{eff} is the effective moisture diffusivity, m^2/s; M, the moisture content, g water/g dry matter and A,B,C,D= constants of regression for microwave-convective and convective drying of garlic slices in different drying conditions are presented in Table 2. The high values of (R^2) in both methods are indicative of good fit of empirical relationship to represent the variation in D_{eff} with M of garlic cloves during drying under different conditions.



Fig(8) Variation in effective moisture diffusivity with moisture content at various air temperature and sample thickness of 5mm, in convective drying.



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Fig(9) Variation in effective moisture diffusivity with moisture content at various air temperature and microwave power of 100 W and sample thickness of 7mm, in microwave-convective drying.

4-4-Activation energy

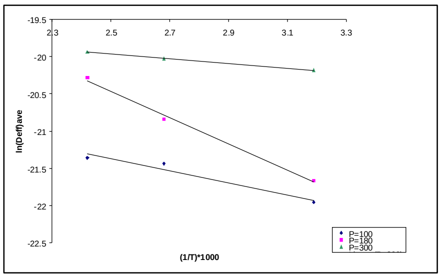
The average effective moisture diffusivity, $(D_{eff})_{avg}$, was calculated by taking the arithmetic mean of the effective moisture diffusivities that were estimated at various levels of moisture contents during the course of drying.

The dependence of average effective moisture diffusivity $(D_{eff})_{avg}$ on drying air temperature was obtained by the Arrhenius-type relationship (Eq. (15))

$$(D_{eff})_{avg} = D_0 \exp\left(\frac{-E_0}{RT_{abs}}\right) \qquad (15)$$

Where: $(D_{eff})_{avg}$ is the average effective moisture diffusivity, m^2/s; D_0, the constant equivalent to diffusivity at infinite temperature, m^2/s; E_a, the activation energy, kJ/mol; R, the universal gas constant, 8.314 $kJ/kgmol\,K$ and T_{abs} is the absolute drying air temperature, K.

The influence of drying air temperature on moisture transport, for microwave-convective method at a microwave power of 100,180 and 300W is shown in figs. (10) and (11) for thicknesses of 5and 7mm, respectively also for convective method this influence has been showed in figs. (12) and (13) for thickness of 5and 7mm, respectively. The activation energies involved in both methods, under different drying conditions, was estimated from slopes of Eq. (15) which ranged between 2.64 and 14.67 kJ/mol in microwave-convective drying and in convective drying between 16.38 and 18.84 kJ/mol for thickness of 5and 7mm, respectively. These are presented in Tables 3 and 4. Thermodynamically, activation energy is the relative ease with which the water molecules pass the energy hurdle when migrating within the product. The lower activation energy translates into higher moisture diffusivity in the drying process. The activation energy in the processes was much lower than the convenctionally heating activation energy values presented in this paper and also lower than values for moisture diffusivity for vegetables ranging between 130 and 280 kJ/mol (Feng & Tang, 1999)[5]. In microwave-convective method the reduction in the energy of activation of a process results from an increase in the average energy of the molecules, which take part in the process. This view is predicted by the thermodynamics of polarized systems, which indicate that microwaves, through polarization, provide additional energy to the dipolar molecules they polarize.



Fig(10) Influence of drying air temperature on average effective moisture diffusivity in microwave-convective drying of garlic cloves at sample thickness of 5mm.

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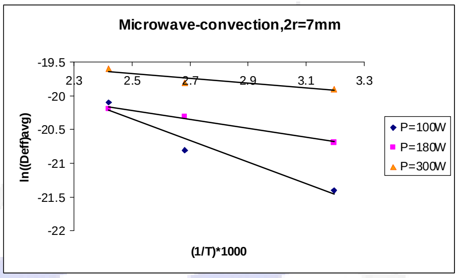

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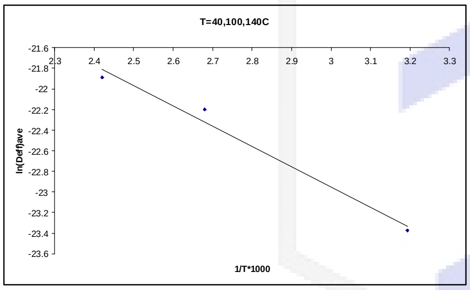
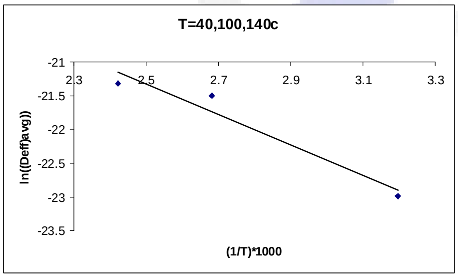
Fig(11) Influence of drying air temperature on average effective moisture diffusivity in microwave-convective drying of garlic cloves at sample thickness of 7mm



Fig(12) Influence of drying air temperature on average effective moisture diffusivity in convective drying of garlic cloves at sample thickness of 5mm



Fig(13) Influence of drying air temperature on average effective moisture diffusivity in convective drying of garlic cloves at sample thickness of 7mm

4-2-Evaluation of models

Tables 5 and 6 shows results of non-linear regression analysis of fitting of the five semi-theoretical models and the developed model to the experimental data and evaluation criteria used to compare the statistical validity of the fit, i.e. (R^2),(RMSE) , and (SSE) at 100 °C air temperature and a sample thickness of 5mm for microwave-convective and convective drying , respectively. All models gave a good fit to the experimental data with a value for R^2 of greater than 0.99. However the values for RMSE obtained from the two-term, page, verma and the developed models are less that 0.025 for all experimental conditions, which is in the acceptable range. The developed model shows the same result

too. But, these models gave a higher value of (R^2) and lower values for the (RMSE) and (SSE) as compared to other models. Hence, the developed model was considered as the best model to predict the dehydration characteristics of garlic slices in both methods within the experimental range of study
Figure (14) and (15) presents the comparison of experimental and predicted moisture ratio using the developed model at various air temperatures and a sample thickness of 5mm in microwave-convective and convective drying, respectively. It can be seen from this; there was a good agreement between experimental and predicted moisture ratios. This indicates the suitability of the developed model in describing dehydration characteristics of garlic slices.

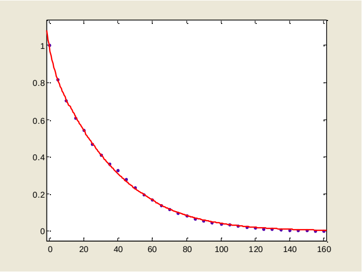


Fig (14) presents the comparison of experimental and predicted moisture ratio using the developed model at 40 °C , P=100 W and a sample thickness of 5mm

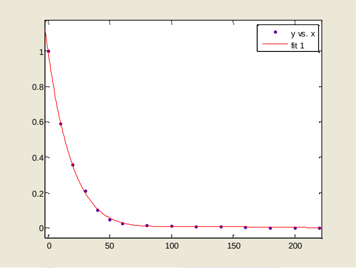


Fig (15) presents the comparison of experimental and predicted moisture ratio using the developed model at 140 °C air temperature in convective drying at sample thickness of 5mm

5-Conclusions

(1) Most garlic dehydration took place in the falling rate drying period.

(2) Dehydration characteristics of garlic slices were affected by air temperature and sample thickness. In microwave-convection technique the power would also affect those characteristics. Increase in the air temperature and decrease in sample thickness, and in combined method, an increase in power caused a decrease in the drying time and an increase in the dehydration rate.

(3) Effective moisture diffusivity (D_{eff}) depends on the moisture content, and in both techniques it increases with decrease in moisture content.

(4) All the five commonly used semi-theoretical models namely, the Henderson and Pabis, two-term, Lewis, Page and Verma were accurate for describing dehydration characteristics of garlic slices. However, the two-term, Page and Verma models were considered as the best model since the RMSE was found to have lower value compare to the others.

(5) The conducted regression analysis, based on non-linear regression methods, tested six thin-layer drying models capability to efficiently simulate convection and microwave-convection drying of garlic slices for the experimental range of the applied temperature, sample thickness and microwave power values. Regression coefficients for all above models were calculated and assessed in terms of fitting performance. The drying model assessment revealed that the developed model exhibited the best performance in fitting the experimental data.

Table (1) Regression coefficient of determination(r^2)under different drying conditions for both techniqucs.

MW power(W)	Temperature (°C)	A_0	A_1	A_2	r^2
100 (2r=5mm)	40	-0.2642	-0.0134	-0.0002	0.988
	100	-0.0513	-0.0548	-0.0001	0.997
	140	-0.0078	-0.0280	-0.0006	0.996
180 (2r=5mm)	40	-0.1634	-0.0324	-0.0006	0.9896
	100	0.2031	-0.0999	-0.0003	0.975
	140	-0.5243	-0.0184	-0.0057	0.958
300 (2r=5mm)	40	0.1303	-0.2148	-0.0002	0.984
	100	-0.0667	-0.3786	-0.0057	0.980
	140	-0.0058	-0.2512	-0.0006	0.993
100 (2r=7mm)	40	-0.3504	-0.0050	-0.0001	0.9593
	100	-0.3938	-0.0093	-0.0009	0.9508
	140	-0.0076	-0.0064	-0.0032	0.9472

180 (2r=7mm)	40	-0.3938	-0.0093	-0.0009	0.9508
	100	0.1372	-0.0832	-0.0005	0.9848
	140	-0.5246	-0.0183	-0.0057	0.9578
300 (2r=7mm)	40	0.1303	-0.2148	-0.0002	0.9841
	100	-0.0671	-0.3786	-0.0057	0.98
	140	-0.0060	-0.2512	-0.0060	0.9928

Thickness	Temperature ($^\circ C$)	A_0	A_1	A_2	r^2
(2r=5mm)	40	-0.2371	-0.0071	-0.0000	0.9898
	100	-0.0517	-0.00337	0.0000	0.9977
	140	-0.2186	-0.0640	0.0002	0.9723
(2r=7mm)	40	-0.1793	-0.0035	-0.0000	0.9828
	100	-0.1982	-0.0299	0.0000	0.9933
	140	-0.2982	-0.0522	0.0001	0.9779

Table(2) Regression coefficients of effective moisture diffusivity during drying conditions for both techniqucs.

MW power(W)	Tempreture ($^\circ C$)	A	B	C	D	r^2
100 (2r=5mm)	40	0.0542	-0.1767	0.2068	-0.0754	0.884
	100	0.0842	-0.2049	0.1861	-0.0536	0.943
	140	0.0999	-0.3668	0.4707	-0.1886	0.918
180 (2r=5mm)	40	0.1081	-0.2869	0.2981	-0.1003	0.935
	100	0.1440	-0.4195	0.4077	-0.1207	0.874
	140	0.0302	-0.2158	0.5547	-0.4032	0.835
300 (2r=5mm)	40	-0.0122	-0.0605	0.1206	-0.0627	0.945
	100	0.0023	-0.0016	0.0409	-0.1735	0.992
	140	0.0036	-0.0585	0.2567	-0.2432	0.944
100 (2r=7mm)	40	0.0779	-0.1959	0.1851	-0.0567	0.905
	100	0.0258	-0.1104	0.1737	-0.0866	0.8884
	140	0.0367	-0.1178	0.1370	-0.0514	0.9564
180 (2r=7mm)	40	0.2051	-0.6285	0.6585	-0.2124	0.8025
	100	0.2731	-0.8557	0.9218	-0.3066	0.8941
	140	0.1331	-0.1036	0.0290	-0.0536	0.9502
300 (2r=7mm)	40	-0.0047	0.4156	-3.7478	6.8523	0.9976
	100	-0.0325	1.0435	-3.5848	1.8182	0.9887
	140	0.0520	-0.2745	0.4872	-0.2415	0.8516

Thickness	Tempreture ($^\circ C$)	A	B	C	D	r^2
(2r=5mm)	40	0.1337	-0.5165	0.1905	-0.0814	0.874
	100	0.0394	-0.1394	0.2912	-0.3264	0.935
	140	0.0465	-0.1945	0.7295	-0.1277	0.912
(2r=7mm)	40	0.0233	-0.0908	0.1327	-0.0631	0.957
	100	0.0736	-0.1368	0.1041	-0.0277	0.800
	140	0.0867	-0.3399	0.4440	-0.1680	0.868

Table(3) Activation energy (E_a) for MW-convective drying processes.

Thickness	Power	Activation energy
2r=5mm	100	10.67
	180	6.71
	300	2.64
2r=7mm	100	13.37
	180	7.53
	300	2.998

Table(4) Activation energy (E_a) for convective drying.

Thickness	Activation energy
5mm	16.38
7mm	18.84

Table(5) Parameter equation of the five semi-theoritical models fitted to the experimental dehydration data of garlic slices at an air tempreture of 100'c, microwave power of 180W and a sample thickness of 5mm in MW-convective drying.

	Henderson & Pabis	**Two-term**	**Lewis**	**Page**	**Verma**	**Developed model**
a	**0.387**	0.365			0.935	0.451
$K, \min^{-1}$	**0.894**	0.899	0.409	0.876	0.413	0.348
b		0.954			0.538	0.983
$K_0, \min^{-1}$		0.669				
m				0.209		0.953
r^2	**0.9952**	0.9962	0.9952	0.9961	0.9973	0.9991
RMSE	**0.02366**	0.02409	0.02252	0.02132	0.01502	0.01179
SSE	**0.005037**	0.004063	0.00507	0.004089	0.003009	0.0009729

Table(6) Parameter equation of the five semi-theoritical models fitted to the experimental dehydration data of garlic slices at an air tempreture of 100'c and a sample thickness of 5mm in convective drying.

	Henderson & Pabis	**Two-term**	**Lewis**	**Page**	**Verma**	**Developed model**
a	0.203	0.546			0.273	0.983
$K, \min^{-1}$	0.201	0.613	0.351	0.676	0.261	0.220
b		0.729			0.149	0.771
$K_0, \min^{-1}$		0.6				
m				0.686		0.198
r^2	0.9996	0.9996	0.9996	0.9997	0.9995	0.9999
RMSE	0.0004682	0.0004465	0.0004745	0.0003471	0.00061	0.000061
SSE	0.006371	0.006001	0.005822	0.005167	0.0029	0.0021

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