Electronic Journal of Polish Agricultural Universities (EJPAU) founded by all Polish Agriculture Universities presents original papers and review articles relevant to all aspects of agricultural sciences. It is target for persons working both in science and industry,regulatory agencies or teaching in agricultural sector. Covered by IFIS Publishing (Food Science and Technology Abstracts), ELSEVIER Science - Food Science and Technology Program, CAS USA (Chemical Abstracts), CABI Publishing UK and ALPSP (Association of Learned and Professional Society Publisher - full membership). Presented in the Master List of Thomson ISI.

ELECTRONIC JOURNAL OF POLISH AGRICULTURAL UNIVERSITIES

2013
Volume 16
Issue 4

Topic:
Food Science and Technology

Chayjan R. , Alaei B. 2013. CHARACTERISTICS OF THIN LAYER MICROWAVE DRYING OF APRICOT, EJPAU 16(4), #12.
Available Online: http://www.ejpau.media.pl/volume16/issue4/art-12.html

CHARACTERISTICS OF THIN LAYER MICROWAVE DRYING OF APRICOT

Reza Amiri Chayjan, Behnam Alaei
Department of Biosystems Engineering, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran

ABSTRACT

Characteristics of thin layer microwave drying of apricot slices were evaluated in a laboratory scale microwave dryer. The drying experiments were carried out at 90, 270, 450, 630 and 900 W. Drying behaviors of apricot slices as well as the effect of drying conditions on moisture loss trend, drying rate, effective diffusion coefficient, color, shrinkage and energy consumption of apricot slices dried in microwave dryer are discussed in this study. Six mathematical models were used to predict the moisture ratio of the samples in thin layer drying. Results showed that the Midilli model had supremacy in prediction of apricot slices drying behavior. The maximum drying rate for various microwave power were 1.42 and 2.70 $g_{water}/g_{dry\ matter}$.min. Effective moisture diffusivity was estimated in the range of 1.64×10^{-9} to 1.07×10^{-8} m^2/s. Minimum total color difference (21.82) and shrinkage (53.03%) were achieved at microwave power 90 W. Energy consumption of the experiments was estimated to be in the range of 0.038 to 0.057 kWh and the model was proposed to determine appropriate microwave power for drying of apricot slices.

Key words: apricot, microwave dryer, moisture diffusivity, color, shrinkage.

INTRODUCTION

Apricot (*Prunus armeniaca* L.) fruits can be used as fresh, dried or processed fruit. Dried apricots are a good source of vitamin A, iron and sugar [18]. Apricot trees can grow over the five continents of the world and production level exceeds two million tons. Australia, France, Hungary, Iran, Italy, Morocco, Spain, Tunisia, Turkey can be regarded as important apricot producer countries. While some countries such as Hungary, Morocco and Tunisia are important fresh apricot importers, the others such as Australia, Iran and Turkey are major and famous dried apricot producers and exporters. Dried apricots which are in extensive demand in several parts of the world, i.e., USA, UK, Germany, Australia, etc., occupy an important place in the world trade [22].

Because of the short harvest season and the sensitivity to storage even under refrigerated conditions, most fresh apricots are preserved in some form. Drying is among the methods which are commonly used. Sun drying permits one to produce a product with a rich orange color, a translucent appearance and a desirable gummy texture. However, it requires a long drying time, affected by daily weather conditions making it rather difficult to control the moisture content of the sample [24]. In addition, product may be degraded during sun drying due to infestation by insects, rodents and other animals and wind-borne dirt and dust [20].

Microwave drying is one of the most interesting methods for drying materials. In the electromagnetic spectrum the microwave radiation region is located between infrared radiation and radio waves. Microwaves have wavelengths of 1 mm to 1 m, corresponding to frequencies between 0.3 and 300 GHz. Telecommunication and microwave radar equipment occupy many of the band frequencies in this region. In general, in order to avoid interference, the wavelength at which industrial and domestic microwave apparatus intended for heating operates is regulated to 12.2 cm, corresponding to a frequency of 2.245 ± 0.05 GHz, but other frequency allocations do exist [22].

In comparison with conventional heating, microwaves offer different heating capacities without requiring a medium as an apparatus for heat transfer. The basic physical phenomenon responsible for the heating of food materials at microwave frequencies is dipole rotation. This phenomenon causes a higher loss of water than most solids because regions with higher water contents within the material absorb more microwave energy [8].

It is generally observed that the pattern of power absorption in a food heated in a microwave oven depends on the power of microwave oven and moisture of food factors, thus it could be concluded that the heating process is directed by heat and mass transfer mechanisms [12]. The application of microwaves solely can result in uneven heating of certain products, depending on their dielectric and thermo-physical properties and inhomogeneous field distribution [1].

Heterogeneous heating of microwave on products such as apricot with high value of sugar and sensitive materials to heat cause burn and chemical reactions. On the other hand, when drying apricot the final moisture content must be less than 16–18% (by weight) [38]. Much reduced final moisture of dried apricot causes reduced water activity, inactivate enzymes, and restrains deteriorative microbial growth [23, 26].

The overall goal of this project is production of crisp chips of apricot, as a light snack without primary chemical treatment and food additive, with low thickness and moisture. Therefore drying behavior of apricot chips as well as the effect of drying conditions on moisture loss, drying rate, effective moisture diffusivity, color, shrinkage and energy consumption of apricot chips dried in microwave dryer are discussed in this study.

MATERIAL AND METHODS

Sample preparation

Fresh apricot samples were procured from a market of Hamedan, Iran. After thorough cleaning and washing, the apricots were cut into 1.2 mm thickness. Air relative humidity and ambient air temperature of laboratory were 28±4% and 28±3°C, respectively. Initial moisture content of apricot was determined using the gravimetric method at 70°C for 24 h [5]. Initial moisture content of apricot was 6.38 (d.b.). Final moisture content of apricot chips after drying process was about 0.09 (d.b.).

Experimental setup

Drying experiments were conducted using a domestic microwave oven (Sharp, R959SLMA, Thailand). This device was designed to dry samples with control of the air temperature and microwave power. Air temperature during the test was 40°C. Five microwave power levels of 90, 270, 450, 630 and 900 W were applied in this study. Average air velocity in the microwave oven was 1.3 m/s.

Humidity was measured by a hygrometer (Lutron, TM-903, Taiwan) with accuracy of ±3% RH. The sample weight during the experiments was recorded using a digital balance (AND, GF-6000, Japan) with±0.01 g accuracy. A flatbed color image scanner (HP, Scanjet G4050, USA) was used for color determining with 1200 DPI setting.

Modeling of drying kinetics

Moisture ratio during thin layer drying of apricot slices was calculated as follows:

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

Equilibrium moisture content (M_e) of samples in each temperature and relative humidity was relatively small compared to M or M_0 [7]. Therefore $(M - M_e)/(M_0 - M_e)$ can be simplified as follow:

$$MR = \frac{M}{M_0} \qquad (2)$$

Drying curves were fitted with six different moisture ratio models (Tab. 1). These models are generally achieved by simplifying the general series solution of Fick's second law and considering a direct relationship between the drying time and average moisture content [18]. Three different criteria considered for evaluation of best fit: determination coefficient (R^2), chi square (χ^2) and root mean square error ($RMSE$) [15].

$$R^2 = 1 - \frac{\sum_{i=1}^{N} [MR_{\exp,i} - MR_{pre,i}]}{\sum_{k=1}^{N} \left[MR_{pre,i} - \frac{\sum_{k=1}^{n} MR_{pre,i}}{N} \right]} \qquad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-z} \quad (4)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2\right]^{\frac{1}{2}} \quad (5)$$

Where $MR_{\exp,\,i}$ is the experimental moisture ratio of ith data, $MR_{\text{pre},\,i}$ is the predicted moisture ratio of i^{th} data, N is the number of observations and z is the number of drying constants.

Drying rate

The drying rate of apricot slices during the thin-layer drying experiments were calculated using the following formula:

$$Dryingrate = \frac{M_{t+dt} - M_t}{dt} \quad (6)$$

Where t is the drying time (min), M_t and M_{t+dt} are the moisture content at time t and $t + dt$ ($kg_{water}/kg_{dry\ matter}$), respectively dt is infinitely small change in time.

Effective moisture diffusivity

Fick's second law of diffusion, symbolized as a mass diffusion for drying agricultural products in a falling rate period, is shown in the following formula:

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \quad (7)$$

By using appropriate initial and boundary conditions, gave the analytical solutions for various geometries and the solution for slab object with constant diffusivity is given as [14]:

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

Where D_{eff} is the effective moisture diffusivity (m^2/s), L is the half thickness of samples (m) and n is a positive integer. For long drying times, only the first term (n=0) in the series expansion of the above equation can give a good estimate of the solution, which is expressed in logarithmic forms as follows [11]:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2}{4L^2}D_{eff}t\right) \quad (9)$$

The diffusion coefficients are typically determined by plotting experimental drying data in terms of ln(MR) versus drying time (t), because the plot gives a straight line with a slope as:

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \quad (10)$$

Color measurements

Most commercial color measurement instruments are not well suited for food engineering research, because they are designed mainly for quality control. This paper presents a simple method that uses a flatbed scanner to measure color and the graphics software Photoshop to analyze color. The term "measure" means that the flatbed scanner is used to obtain the color values of the pixels on the food surface. The term "analyze" means that Photoshop is used to manipulate those color values to obtain color distribution, averages, and so on. In similar studies, this method was used for color determining of pizza [42] and examine food structure [36].

In quantitative analysis, $L^*a^*b^*$ values were used because they are device independent and cover a larger gamut than RGB and CMYK. Photoshop can display *Lab* values (also RGB and CMYK values) in the Info Palette and Histogram Window. The Lightness, a, and b in the Histogram Window are not standard color values. However, they can be converted to $L^*a^*b^*$ values using the formulas [42]:

$$L^* = \frac{Lightness}{255} \times 100 \quad (11)$$

$$a^* = \frac{240a}{255} - 120 \quad (12)$$

$$b^* = \frac{240b}{255} - 120 \quad (13)$$

The total color change (ΔE) (Eq. 14) was calculated from the $L^*a^*b^*$ values and used to describe the color change during drying:

$$\Delta E = \sqrt{\left(L_0^* - L_t^*\right)^2 + \left(a_0^* - a_t^*\right)^2 + \left(b_0^* - b_t^*\right)^2} \quad (14)$$

Where $L_0{}^*a_0{}^*b_0{}^*$ are the initial color measurements of apricot slices and $L_t{}^*a_t{}^*b_t{}^*$ are the color measurements at specified time.

Shrinkage

Volume ratio of the samples due to shrinkage during drying was calculated according to the formula [17]:

$$V_R = \frac{V(t)}{V_0} \quad (15)$$

Where $V(t)$ is the volume at the instant t (m^3) and V_0 is the initial volume of the sample (m^3). Three basic sizes measured with the use of a digital caliper. Three replications were performed on samples with the same moisture content [21].

Volume of the samples before and after drying was calculated according to the following formulas:

$$V(t) = A(t) \times l(t) \quad (16)$$

Where $A(t)$ is the sectional area of cylinder (m^2) and $l(t)$ is the height of the cylinder (m). $A(t)$ calculated with area of the base was obtained by Photoshop software with cutting around of sample and enumerated the number of image pixels sample and compared number of pixels square unit with area of 1 cm. This method was tested with several coins with different diameter and has a high accuracy. Value of $l(t)$ obtained by digital caliper.

Energy consumption

In microwave dryers, electromagnetic energy is directly converted to kinetic energy of water molecules. Therefore, heat is produced within the product and energy transfer is not affected by transfer impediments especially in viscous materials. As microwaves can penetrate into the material and save energy, in this method heat can be produced in the whole volume of the material, thereby increasing drying rate.

Energy consumption in microwave dryers is equal to [32]:

$$E = MP \times t \quad (17)$$

Where E is the total energy consumed in each drying cycle (kWh), MP is the microwave output power (kW) and t is the drying time (h).

RESULTS AND DISCUSSION

Drying kinetic

Drying curves of apricot samples undergoing microwave drying at various microwave powers are shown in Figure 1. The time required to dry apricot samples from initial moisture content 6.38 (d.b.) to the final moisture content of 0.09 (d.b.) was 27, 8.5, 6.5, 4.5 and 3.83 min at 90, 270, 450, 630 and 900 W, respectively. Drying microwave power had an important effect on drying time. The results indicated that mass transfer within the sample was more rapid during higher microwave power heating because more heat was generated within the sample creating a large vapor pressure difference between the center and the surface of the product due to characteristic microwave volumetric heating. The drying times obtained in this present study was extremely low compared the results obtained in the previous studies given in the literature. Drying time of apricot samples with a cabinet dryer and average radius and weight of 3.81±0.3 cm and 31.23±0.5 g, respectively was reported about 30 to 50 h [18]. The results obtained in this present work showed that as compared to cabinet dryer and complete product, the drying time can be shorter by 112 times by working at microwave output power of 90 W.

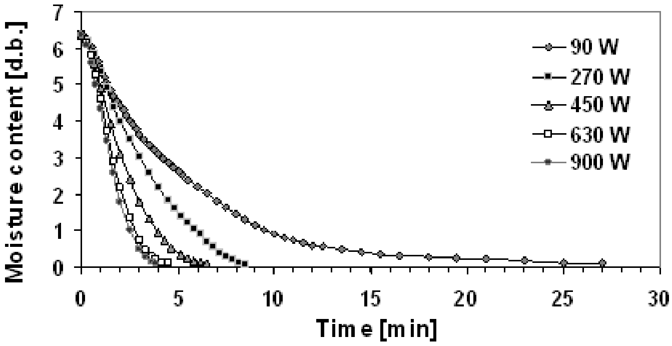

Fig. 1. Variation of the moisture content with drying time at various microwave powers

Drying models

The moisture content data from the drying experiments were converted into the moisture ratio (*MR*) and then fitted to the selected thin layer drying models listed in Table 1. Six different models were evaluated to find the best model for prediction apricot samples moisture ratio. Software of MATLAB R2012a with non-linear regression analysis was used to fit the mathematical models on experimental drying data. The statistical results of the empirical models, including the comparison indices used to evaluate goodness of fit. In the other words, coefficient of determination (R^2), root mean square error (*RMSE*) and reduced chi-square (χ^2) are presented in Figure 2. Based on the criteria of the highest R^2 and the lowest RMSE and χ^2, the best model describing the thin layer drying characteristics of apricot samples was selected.

Table 1. Models employed for fitting of experimental data

No.	Model name	Equation	References
1	Midilli	MR=$a\ exp(-kt^n)+bt$	Midilli *et al.* (2002)
2	Page	MR=$exp(-kt^n)$	Motevali *et al.* (2010)
3	Wang and Singh	MR=$1+at+bt^2$	Wang and Singh (1978)
4	Aghbashlo *et al.*	MR=$exp(-at/(1+bt))$	Aghbashlo *et al.* (2009)
5	Logarhitmic	MR=$a\ exp(-kt)+c$	Wang *et al.* (2007)
6	Demir *et al.*	MR=$a\ exp(-kt)^n+b$	Demir *et al.* (2007)

a, b, c, k and *n* are drying constants

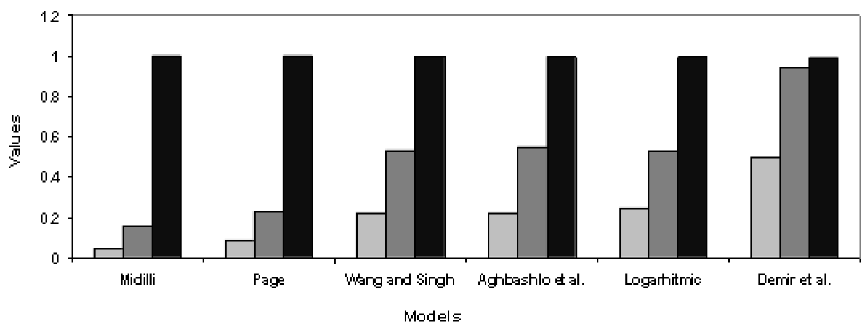

Fig. 2. Average value of R^2, χ^2 and RMSE for used models for fitting of experimental data (█ R^2, █ RMSE/25 and █ χ^2)

For all experiments, the R^2, RMSE and χ^2 values for models changed between 0.9768 and 1, 0.0021 and 0.0751, and 0.0005 and 0.0413, respectively. From Figure 2, the highest R^2 values and the lowest RMSE and χ^2 values were obtained from the Midilli model. The R^2, RMSE, and χ^2 values of Midilli model varied between 0.9991 and 1, 0.0021 and 0.0105, and 0.0005 and 0.0062, respectively. Hence the Midilli model was selected as the suitable model to represent the thin layer drying behavior of apricot samples. Table 2 presents the estimated values of parameters in Midilli model depending on various microwave powers. All the estimated parameters were statistically significant at least at 1% level of significance.

Table 2. Estimated values of Midilli model parameters used for thin layer drying of apricot slices at different microwave powers

Microwave power (W)	a	b	k	n	R^2	$RMSE$	χ^2
90	0.9943	- 0.00005564	0.000365	1.695	0.9999	0.00448	0.00018
270	0.9978	0.00000257	0.000255	1.743	1	0.00209	0.00005
450	1.007	- 0.00003089	0.000848	1.406	0.9998	0.00518	0.00035
630	1.016	- 0.0001723	0.001485	1.184	0.9994	0.00875	0.00153
900	1.018	0.0000062	0.002909	1.013	0.9991	0.01045	0.00622

The Midilli model has also been suggested by others to describe the infrared drying of tomato [13], fluidized bed drying of olive pomace [6, 28], sun, oven, and microwave oven drying of savory leaves and thin layer drying of potato, apple, and pumpkin slices [3].

Drying rates

Drying rate of the apricot samples were calculated using Equation 6. The changes in the drying rates versus drying time for the different powers of microwave are shown in Figure 3. The drying rates increased with the increasing microwave power levels. It is apparent that the drying rate decreases continuously with decreasing moisture content or increasing drying time. The moisture content of the material was very high during the initial phase of the drying which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate. Also the surface heating of slices and generating of high temperature in the surface, cause case hardening and moisture migration will be impressed.

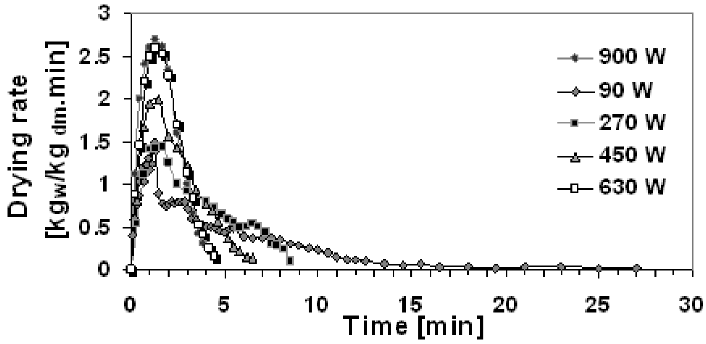

Fig. 3. Variation of drying rate with drying time at various microwave powers.

Drying rate showed a fast increase at the beginning of the process due to microwave heating of the samples and a subsequent decrease, showing two differentiated periods: 1) rapid decreasing of drying rate from a given critical moisture content and 2- drying rate decreased slowly to reach a plateau with a practically constant value, so, drying rate curves showed a sigmoid shape, where the influence of microwave power can be observed in practically the entire range of sample moisture content. Nevertheless, at a higher power level, the initial rates are more greatly enhanced. Similar result has been reported in drying of orange slices [33] and mint leaves [25].

Effective moisture diffusivity

The determined values of effective moisture diffusivity (D_{eff}) for different microwave powers are given in Table 3. The values were placed within the general range of 10^{-6} to 10^{-11} m^2/s for food materials [19]. Furthermore, the values of D_{eff} obtained from this study within the range of 1.64×10^{-9} to 1.07×10^{-8} m^2/s. It can be seen that the values of D_{eff} increased with increasing microwave power. This might be explained by the increased heating energy, which would increase the activity of the water molecules leading to higher moisture diffusivity when samples were dried at higher microwave power. Similar results with D_{eff} = 7.04×10^{-8} to 24.22×10^{-8} m^2/s for microwave drying of apple cylinders [41] and = 3.98×10-11 to 2.07×10-10 m2/s for microwave drying of aromatic plants [3] were achieved.

Table 3. Values of effective moisture diffusivity attained for apricot slices under microwave drying

Microwave power (W)	90		270		450		630		900	
Parameters	D_{eff} (m^2/s)	R^2	D_{eff} (m^2/s)	R^2	D_{eff} (m^2/s)	R^2	D_{eff} (m^2/s)	R^2	D_{eff} (m^2/s)	R^2
Values	1.64×10^{-9}	0.9877	4.44×10^{-9}	0.9157	6.33×10^{-9}	0.9710	9.50×10^{-9}	0.9634	1.07×10^{-8}	0.9456

Color

Changes of apricot slices color under different microwave powers are shown in Figure 4. The plot of ΔE coefficient versus microwave power has been presented in Figure 5. Obtain color value $L^*a^*b^*$ with L^* representing the brightness or dullness, a^* for redness to greenness, and b^* for yellowness to blueness by the Equations 11, 12 and 13 and finally total color difference ΔE was then determined using the Equation 14.

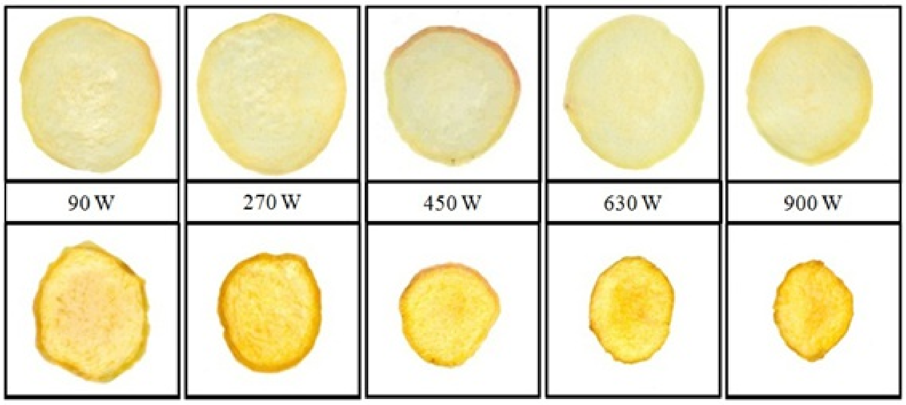

Fig. 4. Changes of color and shrinkage of apricot slices under various microwave powers

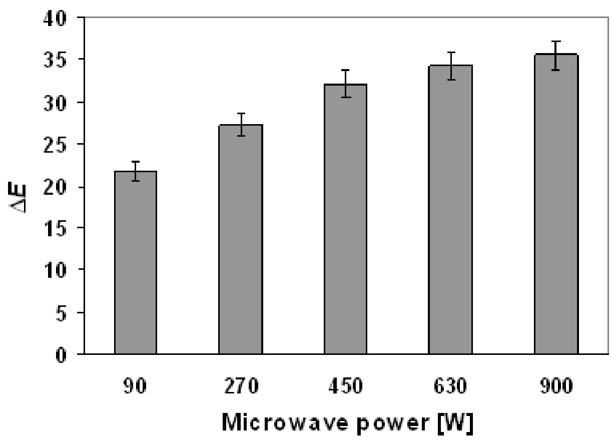

Fig. 5. Variations of total color difference versus microwave powers

Total color change (ΔE) of apricot slices increased significantly during microwave drying with drying time and also ranged from 21.82 to 35.55 as the microwave output power increased from 90 to 900 W, respectively. When food preparations are heat-processed, a number of chemical reactions occur, one of them is the well-known Millard reaction [30], known to be responsible for non-enzymatic browning. The Maillard reaction involves the reaction of an aldehyde (usually a reducing sugar) and an amine (usually a protein or amino acid) and is highly temperature-dependent.

With increasing microwave power, temperature of apricot slices was increased and higher temperature led to increase in degradation processes of pigments [9].

$$\Delta E = 18.27 + 0.0408\times MP - 3.408\times10^{-5}\times MP^2 \qquad R^2 = 0.9980 \qquad (17)$$

This quadratic equation can be predict the ΔE with high precision.

Shrinkage

Changes of shrinkage of apricot slices under microwave powers are shown in Figure 4. The plot of volume ratio versus various microwave powers has been presented in Figure 6. In each case, three samples were used and the average values were considered. The final volume ratio was varied from 0.53 to 0.16 for 900 and 90 W, respectively.

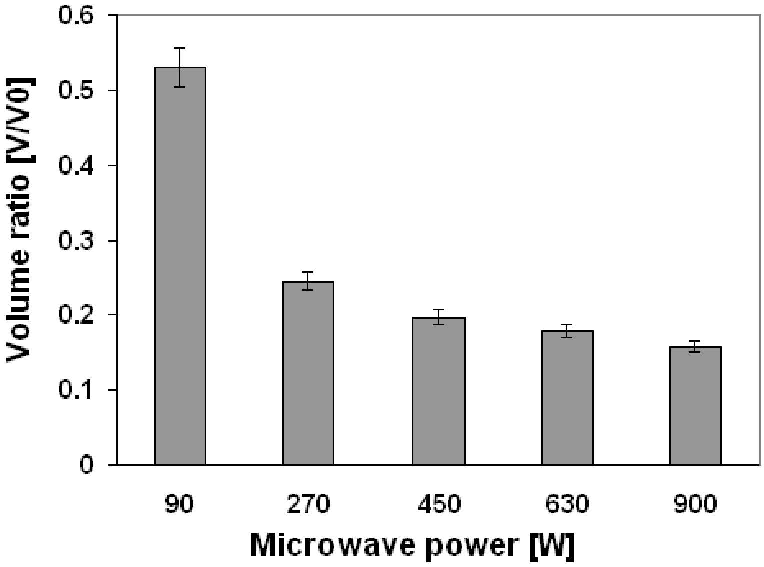

Fig. 6. Variations of volume rate versus microwave powers

Mass transfer in microwave heating, such as other heating methods is from inside to the surface of material. But unlike the convective drying, the heat is generated inside the material. When water is gradually removed from a foodstuff, a pressure unbalance is generated between the inner of the material and the external pressure, creates contracting stresses that lead to material shrinkage or collapse, changes in shape and occasionally cracking of the product [27]. At higher power microwave creates shrinkage increased because engender more heat in apricot samples. Similar behavior has been observed on apple drying [35], potato drying [39] and drying of carrot and garlic [37]. Regression relationship between volume ratio and microwave power was proposed in the form:

$$V_R = 0.763 - 0.0031 \times MP + 5.206 \times 10^{-6} \times MP^2 - 2.827 \times 10^{-9} \times MP^3 \qquad R^2 = 0.9932 \qquad (18)$$

Energy consumption

Energy consumption was calculated using Equation 17. The plot of total energy consumption at various microwave powers is presented in Figure 7. Total energy consumption of the experiments was estimated in the range 0.038 to 0.057 kWh. Minimum and maximum energy consumption of microwave power was 270 and 900 W respectively. Similar result has been reported in drying of pumpkin slices [4] and cranberries [10]. Microwave drying is an inexpensive method that consumes less energy than other drying methods. This is due to the increased presence of bipolar water molecules at higher microwave powers, which results in more energy being absorbed from microwaves generating heat and thus increasing the sample temperature. Similar results were reported by researchers for other crops [32, 34].

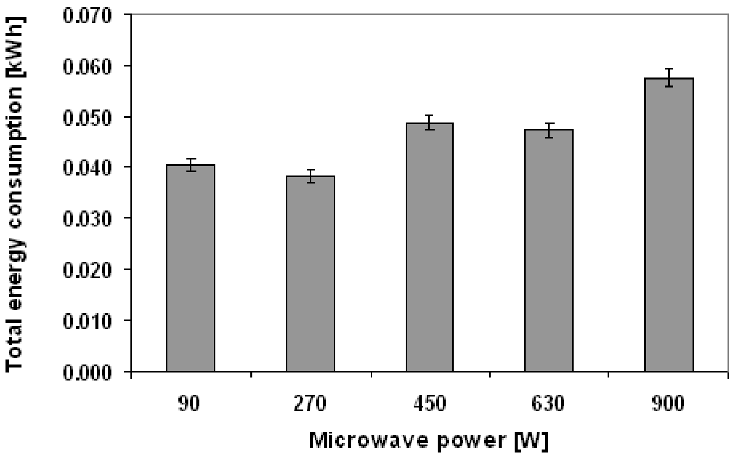

Fig. 7. Variations of total energy consumption versus microwave power

CONCLUSION

Microwave drying is an appropriate method for apricot chips production. Characteristics of the microwave drying of apricot slices (about 1.2 mm of sample thickness) were determined. The required time to dry apricot samples from initial moisture content of 6.38 (d.b.) to the final moisture content of 0.06 (d.b.) was 27, 8.5, 6.5, 4.5 and 3.83 min at 90, 270, 450, 630 and 900 W, respectively. This study indicated that based on non-linear regression analysis, the Midilli model gave excellent fitting to the drying experimental data on drying apricot slices. The drying time of apricot slices decreased and the effective diffusivity increased as the microwave output power increased. The values of effective diffusivity for microwave drying of apricot slices in the range of 4.10×10^{-10} to 2.68×10^{-9} m^2/s were calculated. Total color difference and shrinkage of apricot samples under microwave drying increased with increasing of microwave power. Minimum (0.038 kWh) and maximum (0.057 kWh) energy consumption was achieved at microwave powers 270 W and 900 W, respectively.

REFERENCES

1. Abbasi Souraki B., Mowla D., 2008. Simulation of drying behaviour of a small spherical foodstuff in a microwave assisted fluidized bed of inert particles. Food Research International, 41, 255–265.
2. Aghbashlo M., Kianmehr M.H., Khani S., Ghasemi M., 2009. Mathematical modeling of thin-layer drying of carrot. International Agrophysics. 23. 313–317.
3. Akpinar E., 2006. Determination of suitable thin layer drying curve model for some vegetables and fruits. Journal of Food Engineering, 73, 75–84.
4. Alibas I., 2006. Microwave, air and combined microwave-air-drying parameters of pumpkin slices. Food Science and Technology, 40, 1445–1451.
5. AOAC., 2002. Official methods of analysis. Association of Official Analytical Chemists Arlington, USA.
6. Arslan D., Ozcan M., 2011. Evaluation of drying methods with respect to drying kinetics, mineral content, and color characteristics of savory leaves. Food and Bioprocess Technology, 5 (3), 983–991.
7. Arumuganathan T., Manikantan M.R, Rai R.D., Anandakumar S., Khare V., 2009. Mathematical modeling of drying kinetics of milky mushroom in a fluidized bed dryer. International Agrophysics, 23(1), 1–7.
8. Askari G.R., Emam-Djomeh Z., Mousavi S.M., 2013. Heat and mass transfer in apple cubes in a microwave-assisted fluidized bed drier. Food and Bioproducts Processing, 91, 207–215.
9. Bal L.M., Kar A., Satya S., 2011. Kinetics of colour change of bamboo shoot slices during microwave drying. International Journal of Food Science & Technology, 46, 827–833.
10. Beaudry C,. Raghavan G.S.V., Rennie T.J., 2003. Microwave finish drying of osmotically dehydrated cranberries. Drying Technology, 21:9, 1797–1810.
11. Belma O., Gokce D., 2007. Thin-layer drying characteristics and modelling of mint leaves undergoing microwave treatment. Journal of Food Engineering, 83, 541–549.
12. Bilbao-Sainz C., Andres A., Chirlat A., Fito P., 2006. Microwave phenomena during drying of apple cylinder. Journal of Food Engineering, 74, 160–167.
13. Celma A., Cuadros F., Rodriguez L., 2008. Characterisation of industrial tomato by-products from infrared drying process. Food and Bioproducts Processing, 87, 282–291.
14. Crank J., 1975. The Mathematics of Diffusion. Clarendon Press, UK, Oxford.
15. Demir V., Gunhan T., Yagcioglu A.K, Degirmencioglu A., 2004. Mathematical modeling and determination of some quality parameters of air-dried bay leaves. Biosystems Engineering, 88(3), 325–335.
16. Demir V., Gunhan T., Yagcioglu A.K., 2007. Mathematical modelling of convection drying of green table olives. Biosystems Engineering, 98, 47–53.
17. Dissa A.O., Desmorieux H., Savadogo P.W., Segda B.G., Koulidiati J., 2010. Shrinkage porosity and density behaviour during convective drying of spirulina. Journal of Food Engineering, 97, 410–418.
18. Doymaz I., 2004. Effect of pre-treatments using potassium metabisulphite and alkaline ethyl oleate on the drying kinetics of apricots. Biosystems Engineering, 89(3), 281–287.
19. Doymaz I., 2005. Drying behavior of green beans. Journal of Food Engineering, 69, 161–165.
20. El-Beltagy A., Gamea G.R., Amer Essa A.H., 2007. Solar drying characteristics of strawberry. Journal of Food Engineering, 78, 456–464.
21. Figiel A., 2010. Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. Journal of Food Engineering, 98, 461–470.
22. Karatas F., Kamisli F., 2007. Variations of vitamins (A, C and E) and MDA in apricots dried in IR and microwave. Journal of Food Engineering, 78, 662–668.
23. Krokida M.K., Maroulis Z.B., Saravacos G.D., 2001. The effect of the method of drying on the colour of dehydrated products. International Journal of Food Science and Technology, 36, 53–59.
24. Lee W.Y., Cha W.S., Oh S.L., Cho Y.J., Lee H.Y., Lee B.S., 2006. Quality characteristics of dried radish (Raphanus sativus) by drying methods. Korean Journal of Food Preservation, 13, 37–42.
25. Ozbek B., Dadali G., 2007. Thin-layer drying characteristics and modelling of mint leaves undergoing microwave treatment. Journal of Food Engineering, 83, 541–549.
26. Maskan M., 2000. Kinetics of colour change of kiwifruits during hot air and microwave drying. Journal of Food Engineering, 48, 169–175.
27. Mayor L., Sereno A.M., 2004. Modelling shrinkage during convective drying of food materials: a review. Journal of Food Engineering, 61, 373–386.
28. Meziane S., 2011. Drying kinetics of olive pomace in a fluidized bed dryer. Journal of Energy Conversion and Management, 52, 1644–1649.
29. Midilli A., Kucuk H., Yapar Z., 2002. A new model for single-layer drying. Drying Technology, 20(7), 1503–1513.
30. Milton S.F., 1985. Some aspects of the chemistry of non-enzymatic browning (the maillard reaction), in chemical changes in food during processing, edited by Richardson, T, AVI Publishering Co., 289–303.
31. Motevali A., Minaei S., Khoshtaghaza M.H., Kazemi M., Nikbakht, A.M., 2010. Drying of pomegranate arils: comparison of predictions from mathematical models and neural networks. International Journal of Food Engineering, 6(3), 1–20.
32. Motevali A., Minaei S., Khoshtaghaza M.H., Amirnejat H., 2011. Comparison of energy consumption and specific energy requirements of different methods for drying mushroom slices. Energy, 36, 6433–6441.
33. Rııız Dıaz G., Martınez-Monzo P., Chiralt A., 2003. Modelling of dehydration-rehydration of orange slices in combined microwaveyair drying. Innovative Food Science and Emerging Technologies, 4, 203–209.
34. Sami S., Etesami N., Rahimi A., 2011. Energy and exergy analysis of an indirect solar cabinet dryer based on mathematical modeling results. Energy, 36, 2847–2855.
35. Sjoholm I., Gekas V., 1995. Apple shrinkage upon drying. Journal of Food Engineering, 25, 123–130.
36. Stanley D.W., Baker K.W., 2002. A simple laboratory exercise in food structure/texture relationships using a flatbed scanner. Journal of Food Science and Education. Vol. 1.
37. Taner B., Filiz I., Seda E., Hasan Y., 2003. Effects of microwave and infrared drying on the quality of carrot and garlic. European Food Research and Technology, 218, 68–73.
38. Togrul I.T., Pehlivan D., 2003. Modelling of drying kinetics of single apricot. Journal of Food Engineering, 58, 23–32.
39. Wang N., Brennan J.G., 1995. Changes in structure, density and porosity of potato during dehydration. Journal of Food Engineering, 24, 61–76.
40. Wang C.Y., Singh R.P., 1978. A Single Layer Drying Equation for Rough Rice. ASAE Press, St. Joseph, MI, USA.
41. Wang Z., Sun J., Liao X., Chen F., Zhao G., Wu J., Hu X., 2007. Mathematical modeling on hot air drying of thin layer apple pomace. Journal of Food Engineering, 40, 39–46.
42. Yam K.L., Papadakis S.E., 2004. A simple digital imaging method for measuring and analyzing color of food surfaces. Journal of Food

Engineering, 61, 137–142.

Accepted for print: 27.12.2013

Reza Amiri Chayjan
Department of Biosystems Engineering, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran
Postal Code: 6517833131
TEL: (+98) 811 4424014; FAX: (+98) 811 4424012;
amirichayjan@gmail.com
email: amirireza@basu.ac.ir

Behnam Alaei
Department of Biosystems Engineering, Faculty of Agriculture, Bu-Ali Sina University, Hamedan, Iran
Postal Code: 6517833131