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Drying kinetics of ginger (*Zingiber officinale*) slices under going microwave drying

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ABSTRACT : The drying characteristics of ginger slices were investigated in an experimental microwave dryer and modeled at 1.0, 1.5, 2.0 and 2.5 kW power levels. The entire drying process took place in the falling rate period. The effective moisture diffusivity values ranged from 2.5356 × 10^{-11} to 1.2678 × 10^{-9} m^2/s within the power levels (1.0 to 2.5 kW) studied. Exponential, Page, Henderson and Pabis, Logarithmic and Power law models were applied and validated on the basis of determination of coefficient (R^2), reduced mean square (χ^2) of the deviation, mean bias error (E_{MB}) and root mean square error (E_{RMS}) between the observed and predicted values of moisture ratios. Page model was found to fit best, representing an excellent tool for estimation of the drying time and the values of R^2, χ^2, E_{RMS} and E_{MB} were in the ranged of 0.995 to 0.997; 0.0006 to 0.005; 0.022 to 0.038 and 0.005 to 0.009, respectively.

KEY WORDS : Ginger, Moisture diffusivity, Modelling, Microwave, Falling rate, Moisture ratio

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Dehydration is an important preservation process which reduces water activity through the decrease of moisture content, avoiding potential deterioration and contamination during long storage periods. Also, food quality is preserved, the hygienic conditions are improved, and product loss is diminished (Kaymak-Ertekin, 2002). For these reasons, several dehydration methods or combinations of methods can be used including microwave drying, solar drying, hot-air, freeze drying, osmotic dehydration, spray drying, impregnation vacuum, etc. Other important advantages of food dehydration are weight and volume reduction, intended to decrease transportation and storage costs (Okos *et al*., 1992).

Cost-effective and hygienic ways of preserving foods are of great importance given the prevailing insecurity in food supplies throughout the world. The introduction of dryers in developing countries can reduce crop losses and improve the quality of the dried product significantly when compared to the traditional methods of drying such as sun or shade. Therefore, simulation models are needed for the design and operation of dryers. Several researchers have developed simulation models for natural and forced convection drying systems as suggested by Ratti and Mujumdar (1997).

The study of drying behaviour of different materials has been subject of interest for various investigators on both theoretical and application grounds during the past several years. There have been many studies on the drying behaviour of various vegetables and fruits such as mushroom, pollens green pepper, green, bean and pumpkin by Yaldiz and Ertekin (2001) and red pepper by Kaymak-Ertekin (2002). In this study, the thin layer drying behaviour of ginger slices in a microwave dryer has been investigated and various drying models have been validated.

METHODOLOGY

The fresh ginger rhizomes were procured in bulk from the local market of Udaipur in the state of Rajasthan (India) which was, then washed under running water to remove adhering impurities. The ginger rhizomes were hand peeled, cut into slices (5±1 mm thickness) with a sharp stainless steel knife in the direction perpendicular to the vertical axis. Three measurements were made on each slice for ensuring proper thickness.

Measurement of moisture content :

Hot air oven method was used to determine the initial moisture content of the ginger. A pre weighed ginger sample of 15 g was kept in a pre-dried and weighed moisture box in oven at 80ºC for 24 hours (Ranganna, 2002). The dried samples were cooled in desiccators to room temperature and then weighed using electronic balance and moisture content (db) of sample which was expressed as g water/g dry matter was used for calculations.

Microwave dryer :

A laboratory model microwave dryer used in this present investigation has maximum frequency and output of 2450 MHz and 2.5 kW, respectively. The microwave cavities of dimension 700×700×550 mm with three vents of 100 mm diameter are present at top. For increasing uniformity in drying, a circular turntable made up of teflon material having diameter 600 mm, and height of the rim about 120 mm) is used inside the chamber. An air blower provided in microwave dryer which blows the air at velocity of 0.75 to1.0 m/s (cooling media) to cool the magnetron continuously during operation of dryer. The dryer also has a digital control facility at front side to adjust the microwave power and automatic time control.

Experimental procedure :

The dryer was run on no load for 120 sec to set the desired drying condition. Ginger slices of 100$\pm$0.5 g were placed in the microwave cavity uniformly and dried at various power levels. The mass of the sample after pre-specified interval was measured after every 5 min during first hour and at 10 min intervals during rest of the drying period until the mass of the sample reduced to a level corresponding to a moisture content of about 6 % (w.b.). The moisture loss was determined by simple mass balance equations during drying. Three replicates were taken for each experiment for various microwave power levels (1.0, 1.5, 2.0 and 2.5 kW).

Mathematical modelling of drying curves and formulation :

The moisture ratio of ginger slices during microwave drying experiments was calculated using the following equation.

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

where, MR is moisture ratio (dimensionless); M is moisture content (g water per g dry matter) at specified time; M_0 is initial moisture content (g H_2O/g dry matter) and M_e is equilibrium moisture content (g H_2O/g dry matter). Five thin layer drying equations listed in Table 1 were tested to select the best model to describe microwave drying of ginger slices.

The effects of some parameters related to the product or drying conditions such as slice thickness, drying air temperature, relative humidity, etc. were investigated by Yaldiz and Ertekin (2001). Modelling of drying behaviour of different agricultural products often requires the statistical methods of regression and correlation analysis. Linear and non-linear regression models are important tools to find the relationships between different variables, especially, those for which no established empirical relationship exists. In this study, the relationships of the constants of the best suitable model with the drying power levels were also determined.

The regression analysis was performed using SYSTAT-8.0 software. The co-efficient of determination (R^2) was primary criterion for selecting the best equation to describe the drying model. In addition to this, the goodness of fit was determined by reduced mean square of the deviation (χ^2), mean bias error (E_{MB}) and root mean square error (E_{RMS}). For quality fit, R^2 value should be higher and close to one and χ^2, E_{MB} and E_{RMS} values should be low revealed by Demir *et al*. (2004). The above parameters were calculated as follows:

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

$$E_{MB} = \frac{1}{N}\sum_{i=1}^{N}\left(M_{R,pre,i} - M_{R,exp,i}\right) \quad (3)$$

$$E_{RMS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{R,pre,i} - M_{R,exp,i}\right)^2\right]^{1/2} \quad (4)$$

where, $M_{R,exp,i}$ and $M_{R,pre,i}$ are the experimental and predicted dimensionless moisture ratios, respectively; N is the number of observations and z is the number of drying constants.

Moisture diffusivity :

In drying, diffusivity is used to indicate the rapidness of flow of moisture or moisture out of material. In falling rate period of drying, moisture is transferred mainly by molecular diffusion. Karim and Hawaldar (2005) studied that diffusivity is influenced by shrinkage, case hardening during drying, moisture content and temperature of material.

The falling rate period in drying of biological materials is best described by simplified mathematical Fick's second law diffusion as given below :

$$\frac{\delta M}{\delta t} = D\,\frac{\delta^2 M}{\delta X^2} \quad (5)$$

where

D = Diffusion coefficient,

M = Moisture content, g water per g dry matter,

X= Characteristic dimension *i.e.* distance of surface from the centre line of product and

t = Time elapsed during the drying.

The ginger slices were considered as infinite slab as the thickness of the slices *i.e.* 5mm was much less than its diameter about 24mm. Certain assumptions were considered in estimation of moisture diffusivity during drying process, which are given herewith as follows:

– Moisture is initially uniformly distributed throughout the mass of sample.

– Mass transfer is symmetric with respect to the centre.

– Surface moisture content of the sample instantaneously reaches equilibrium with the condition of surrounding air.

– Resistance to the mass transfer at the surface is negligible compared to internal resistance of the sample.

– Moisture transfer is by diffusion only.

– The thickness of the material L was assumed constant throughout the drying process.

The solution of Fick's model for infinite slab was given by Crank (1975) as

$$\mathbf{MR} = \frac{\mathbf{M}-\mathbf{M_e}}{\mathbf{M_0}-\mathbf{M_e}} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[\frac{-(2n+1)^2\pi^2 D_{eff} t}{L^2}\right] \quad (6)$$

where

D_{eff} = Effective diffusivity in m^2/s

L = Characteristic dimension *i.e.* thickness of slab

t = Time elapsed during the drying (s)

The equation can be simplified by neglecting second and other terms. So equation reduced to

$$MR = \left(\frac{M-M_e}{M_0-M_e}\right) = \frac{8}{\pi^2}\exp\left(-\pi^2\frac{D_{eff}\,t}{L^2}\right) \quad (7)$$

Taking logarithm and rearranging the equation (7) as

$$\ln[MR] = \ln\left(\frac{M-M_e}{M_0-M_e}\right) = \ln\frac{8}{\pi^2} - \left(\frac{\pi^2 D_{eff}\,t}{L^2}\right) \quad (8)$$

$$\ln[MR] = -0.21 - \left(\frac{\pi^2 D_{eff}\,t}{L^2}\right) \quad (9)$$

A general form of above eq^n could be written in semi-logarithmic form, as follows

$$\ln(MR) = A - Bt \quad (10)$$

where, A is constant and B is slope.

An experimental value of the effective diffusivity is calculated by plotting experimental drying data in terms of ln (*MR*) versus drying time *t*. It gives a straight line and the slope of the line would be used to measure the moisture diffusivity.

RESULTS AND DISCUSSION

The results of the present study as well as relevant discussions have been presented under following sub heads:

Drying curve :

The initial moisture content of ginger was 85.6 % (wb) and the equilibrium moisture content was 6 % (wb) when no more change in weight during drying was observed. The moisture content versus drying time for ginger slices at selected power levels are shown in Fig. 1. It is apparent that moisture content decreases continuously with drying time. The moisture content after 30 min of drying at 1.0, 1.5, 2.0 and 2.5 kW power level was 73.81, 69.42, 60 and 46.67 % (wb) and after 60 min it was found to be 61.6, 50.34, 34.54 and 15.29 % (wb), respectively. The drying time to reach the equilibrium moisture content for fresh ginger slices were 270, 170, 120 and 90 min at 1.0, 1.5, 2.0 and 2.5 kW, respectively. As indicated in these curves (Fig.1), there was no constant rate period in drying of ginger slices. All the drying process occurred in the falling rate period, starting from the initial moisture content of ginger slice (85.6 % wb) to final moisture content (6 % wb). Diamante and Munro (1993) studied that in the falling rate period the material surface is no longer saturated with water and drying rate is controlled by diffusion of moisture from the interior of solid to the surface.

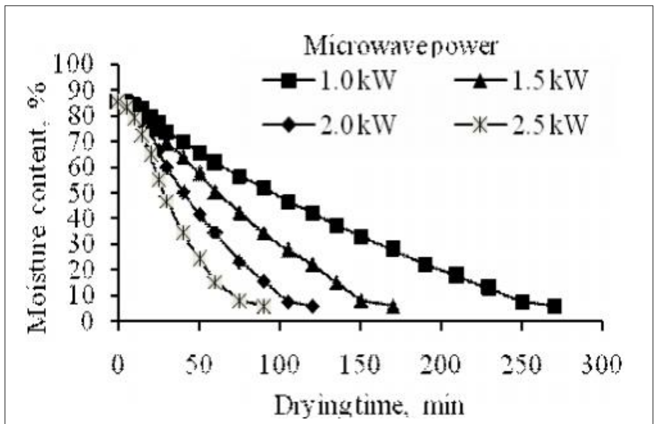

Fig. 1 : Variation in moisture content of ginger slices during microwave drying

Table 1 : Mathematical models widely used to describe the drying kinetics		
Model equation	Name	Reference
MR = exp (-kt)	Exponential	Liu and Bakker-Arkema (1997)
MR = a exp (-kt)	Henderson and Pabis	Henderson and Pabis (1961)
$MR = \exp(-kt^n)$	Page	Zhang and Litchfield (1991)
MR = a + b ln (t)	Logarithmic	Chandra and Singh (1995)
$MR = At^B$	Power law	Chandra and Singh (1995)

Table 2 : Effective moisture diffusivity of ginger slices during microwave drying

Sr. No	Microwave Level (kW)	Diffusivity (m^2/s)	R^2
1.	1.0	2.5356×10^{-11}	0.958
2.	1.5	5.0712×10^{-10}	0.960
3.	2.0	1.0142×10^{-9}	0.976
4.	2.5	1.2678×10^{-9}	0.980

Table 3 : Values of coefficients of model and statistical parameters used in microwave drying of ginger slices

Name of models	Power level (kW)	Drying constant				Statistical parameters			
		k	N	A	b	R^2	χ^2	E_{MB}	E_{RMS}
Exponential	1.0	0.006	-	-	-	0.971	0.003	0.010	0.055
MR=exp (kkt)	1.5	0.010	-	-	-	0.949	0.005	0.013	0.068
	2.0	0.014	-	-	-	0.942	0.006	0.007	0.072
	2.5	0.022	-	-	-	0.930	0.007	0.016	0.080
Henderson and Pebis	1.0	0.007	-	1.077	-	0.984	0.002	0.016	0.041
MR = a exp (-kt)	1.5	0.012	-	1.123	-	0.978	0.003	0.009	0.054
	2.0	0.018	-	1.158	-	0.982	0.004	0.013	0.058
	2.5	0.028	-	1.214	-	0.981	0.007	0.023	0.074
Page	1.0	0.001	1.322	-	-	0.995	0.005	0.006	0.038
MR = exp ($-kt^n$)	1.5	0.001	1.476	-	-	0.997	0.003	0.005	0.032
	2.0	0.002	1.481	-	-	0.996	0.0006	0.009	0.022
	2.5	0.003	1.574	-	-	0.996	0.001	0.005	0.029
Logarithmic	1.0	-	-	1.658	-0.256	0.885	0.033	0.032	0.173
MR = a + b ln (t)	1.5	-	-	1.694	-0.291	0.887	0.044	0.040	0.198
	2.0	-	-	1.708	-0.321	0.889	0.051	0.051	0.209
	2.5	-	-	1.730	-0.363	0.891	0.060	0.061	0.224
Power law	1.0	-	-	2.131	-0.322	0.739	0.075	0.035	0.261
MR = At^B	1.5	-	-	2.223	-0.365	0.731	0.095	0.049	0.289
	2.0	-	-	2.346	-0.416	0.757	0.109	0.061	0.305
	2.5	-	-	2.640	-0.510	0.786	0.124	0.071	0.321

Mathematical modelling of microwave drying curves :

The moisture content data at the different drying power level were converted to the more useful moisture ratio and coefficients of Exponential, Henderson and Pabis, Page, Logarithmic and Power law models were calculated and are presented in Table 3.

It was observed that in all models the values of R^2 were greater than 0.90, indicating a good fit except for power law and logarithmic model. The values of coefficient of determination (R^2) of ginger slices for page model at all power levels were in the range of 0.995 to 0.997 and the values of root mean square error (E_{RMS}), reduced mean square of the deviation (¡²) and mean bias error (E_{MB}) for page model were in the range of 0.022 to 0.038, 0.0006 to 0.005 and 0.005 to 0.009, respectively which were lower than the rest of other four models (Exponential, Henderson and Pabis, logarithmic and power law) used in this study. Fig. 2 represent the variation of experimental and predicted moisture ratio using the Page model with drying time for dried ginger slices. The moisture ratio of the samples decreased continually with drying time. As expected, increase in microwave power levels of drying reduces the time required to reach given level of moisture ratio since the heat transfer increases. In other words, at high microwave power levels

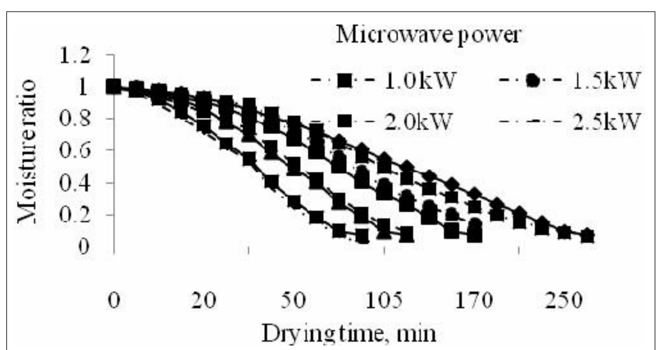

Fig. 2 : Experimental and predicted moisture ratio by the Page model versus drying time

the transfer of heat and mass is high and water loss is excessive. These results are in agreement with drying of tomato by Taheri-Garavand *et al.* **(**2011); mint leaves by Ozbek and Dadali (2007); red pepper by Akpinar *et al*. (2003), dill and parsley leaves by Doymaz *et al*. (2006). It can be seen from the Fig. 3 that there is a good co-relation (R^2 = 0.986) between the observed and the predicted values of moisture ratio.

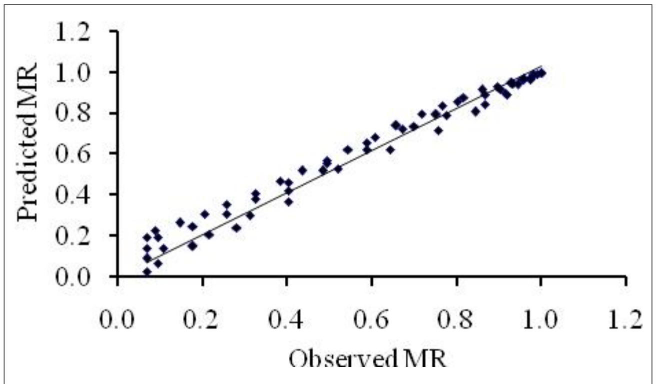

Fig. 3 : Experimental and predicted values of moisture ratio obtained by page model for microwave drying of ginger slices

Moisture diffusivity of samples :

The natural logarithms of moisture ratio (ln MR) were plotted against average drying time (t) for different power levels, and are shown in Fig 4. It was observed from the figure that the relationship was non-linear in nature for all drying conditions. This non-linearity in the relationship might be due to reasons like shrinkage in the product, variation in moisture diffusivity with moisture content and change in product temperature during drying (Kannan and Bandopadhyay, 1995). The non-linearity of the curves, an indicative of the variation in moisture diffusivity with moisture content, was used to estimate effective moisture diffusivity of microwave dried ginger slice samples at corresponding moisture content, under different drying conditions. The moisture diffusivity value of food material was affected by moisture content as well as microwave power level. At lower level of moisture content the diffusivity was less than that at high moisture content. Also it was observed that moisture diffusivity increased with increase in microwave power level in microwave drying process shown in Table 2. The average effective moisture diffusivity $(D_{eff})_{avg}$ values of microwave dried ginger slices varied considerably with moisture content and power level were 2.5356 × 10^{-11} , 5.0712 × 10^{-10} , 1.01424 × 10^{-9} and 1.2678 × 10^{-9} m²/s. These values are within the general range of 10^{-08} to 10^{-12} m²/s for drying of food materials (McMinn and Magee, 1999). These values are in fact consistent with those existing in literature e.g. 3.2 × 10^{-9} to 11.2 × 10^{-9} m²/s for hot air drying of red pepper (Vega-Galveg *et al*. 2007); 1 × 10^{-10} to 2 × 10^{-10} m²/s for hot air drying of blueberries (Ramaswami and Nsonzi, 1998) and 9 × 10^{-10} to 2.33 × 10^{-9} m²/s for hot air drying of parsley leaves (Doymaz *et al.,* 2006).

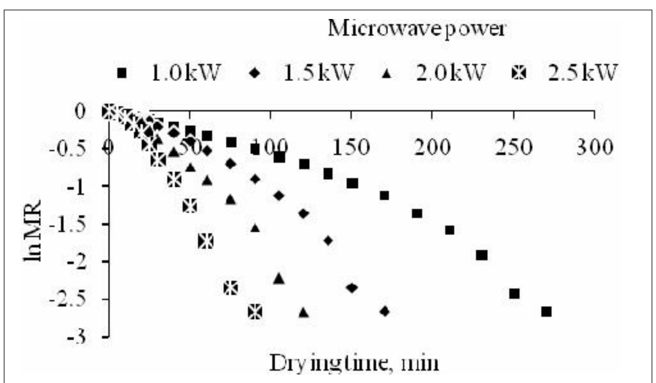

Fig. 4 : Variation in ln (MR) with drying time at different microwave power levels for ginger

Conclusion:

A model to simulate the drying of ginger slices was developed and solved with SYSTAT software. It was observed that microwave drying of ginger slices occurred in the falling rate period and no constant rate period of drying was observed. A good agreement between model predictions and experiments at different power levels was obtained. Page model was found to be the most suitable for describing drying of ginger slices with R^2 of 0.997, χ^2 of 0.0006, E_{MB} of 0.009 and E_{RMS} of 0.022. The effective moisture diffusivities increased from 2.5356 × 10^{-11} to 1.2678 × 10^{-9}m² s⁻¹ with the increase in microwave output power. The results show that the proposed model can be used to optimize the drying process in order to obtain higher quality dried ginger from a flavonoid and organoleptic standpoint.

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