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Estimation of Mass Transfer Parameters and Drying Characteristics of Black Pepper using Microwave Energy

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Abstract-- Drying characteristics of black pepper with an initial moisture content of 59.98% (kg moisture/kg wet sample) was carried out in a domestic microwave oven at five different powers of 900W, 720W, 540W, 360W and 180W. The drying curves were plotted and from the rate vs moisture content curves it could be concluded that the complete drying process had took place in the falling rate period. Experimental data were fitted to the thirteen thin layer drying models available in the literature. Midilli et al model was found to be the best model to describe the microwave thin layer drying of black pepper. The effective diffusivities were estimated by using Fick's second law of diffusion for spherical particles. Mass transfer coefficients and mass Biot numbers were also calculated for the five microwave powers. The effective diffusivities, mass transfer coefficients and the mass Biot numbers varied between 1.144*$10^{-10}$to 4.575*10^{-9} m^2/s, 0.863 to 8.47 m/s and 84.5* 10^5 to 20.7* 10^5 for the microwave powers studied. Effective diffusivities and mass transfer coefficient increased with the increasing microwave power where as the mass Biot numbers decreased with the increasing microwave power.

Keywords: Black pepper, Microwave Energy, effective diffusivity, mass transfer coefficient, Biot number

1. Introduction

Drying is a complicated process involving simultaneous heat and mass transfer. The required amount of energy to dry a particular product depends on many factors, such as initial moisture content, final moisture content, drying air temperature, relative humidity and velocity. Various mathematical models describing the drying behavior of different food materials have been proposed to optimize the drying process and design efficient dryers. Modeling is advantageous because full scale experimentation of different products and configurations of drying system is very time consuming and costly [1]. In order to improve the quality, the traditional natural sun drying must be relaced by modern drying methods. Drying characteristics of specific products should be determined to improve the quality [2].
Black pepper is commonly used spice in cooking. It is also used as herb for its medicinal activity. Drying of pepper is done usually by natural sun drying technique, but this leads to contamination of product by dirt and dust. Therefore, the process should be done in closed equipments. Although many studies have been done on drying of several food materials like sour cherry[3], corn[4], garlic cloves[5]. Microwave thin layer drying study of black pepper is very rare in literature.

The objective of the present study was to determine the drying model suitable for thin layer drying of black pepper, to study the behavior of drying curves and to calculate the mass transfer parameters like effective diffusivity, mass transfer coefficient and the mass Biot number.

2. Materials and Methods

2.1 Materials

Fresh ripened black pepper were obtained from the plant, cleaned and kept in a refrigerator at 4^{o}C before drying. Uniform sizes of pepper were selected for drying operation. To know the radius of the sample, volume displacement method was used and the radius of the pepper was calculated as 0.336cm. Initial moisture content of the sample was determined by using laboratory vacuum oven operated at 105^{o}C for 24 hrs. IMC of the sample was found to be 59.98% wet basis (w.b).

2.2 Experimental set up

Domestic microwave dryer MODEL no MG 607 APR GRILL and an digital electronic balance of accuracy 0.01g, microwave tray and raw black pepper was the experimental setup for microwave thin layer drying of black pepper.

2.3 Drying procedure

The Microwave drying experiments were conducted at 900watts, 720watts, 540watts, 360watts and 180watts. In each experiment, 20 g of ripened black pepper of about 0.336mm radius were used. The microwave was run for 1min and put off and the weight of the sample was checked using the electronic weighing device and noted down. Drying was continued until the sample had no moisture loss. The dried sample was allowed to cool in dessicator for 15 minutes and then it was packed in polythene bags.

2.4 Mathematical modeling

Drying curves obtained from experimental data were fitted to standard thin layer drying models presented in Table 1. The drying of biological materials in the falling rate period is a diffusion-controlled process and may be represented by Fick' s second law of diffusion. Various types of mathematical models were used to describe drying of foodstuffs [6]. The moisture ratios of the samples were calculated by using the following equation:

$$MR = (M-M_e)/(M_0-M_e) \qquad (1)$$

Where M is the moisture content at any time (kg water/kg wet mass), M_0 is the initial moisture content(kg water/kg wet mass), and M_e is the equilibrium moisture content of sample (kg water/kg wet mass). The values of M_e are relatively small compared to M or M_0, hence the error involved in the simplification is neglible [7].
Selected thin layer drying models were fitted to drying curves and the model parameters determined by non linear regression analysis. The goodness of fit was determined by three values, coefficient of determination(R^2), the reduced chi square ($\chi 2$) and root mean square error (RMSE). These parameters can be calculated as follows:

$$\chi 2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N-n} \qquad 2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{i,pre} - MR_{i,exp})^2}{N}} \qquad (3)$$

where, $MR_{exp,i}$ is the i^{th} experimental moisture ratio, $MR_{pre;i}$ is the ith predicted moisture ratio, N is the number of observations, n is the number of constants in drying model. The best model describing the thin layer drying characteristics of black pepper was chosen as the one with highest coefficient of determination and the least reduced chi square and root mean square error [8].

Table 1 Mathematical models applied to drying curves

Model name	Model	References
Newton	MR = exp(-kt)	[9]
Page	$MR = exp(-kt^n)$	[10]
Modified page	$MR = exp[(-kt)^n]$	[11]
Modified page	$MR = exp[-(kt)^n]$	[12]
Henderson & pabis	MR = a exp(-kt)	[13]
Logarithmic	MR = a exp(-kt)+c	[14]
Two term	$MR = a\ exp(-kt)+b\ exp(-k_1t)$	[15]
Two term exponential	MR = a exp(-kt)+(1-a) exp(-k a t)	[16]
Wang & sing	$MR = 1+at+bt^2$	[17]
Diffusion approximation	MR =a exp(-kt)+(1-a) exp(-k b t)	[12]
Verma et al	MR = a exp(-kt)+(1-a) exp(-gt)	[18]
Modified Henderson & pabis	MR=aexp(-kt)+bexp(-gt)+cexp(-ht)	[19]
Midilli et al	$MR = a\ exp(-kt^n)+bt$	[20]

3.Results and discussions

3.1 Drying characteristics of black pepper

Moisture ratio versus time of black pepper drying curve was shown in the Fig.1. It showed that the moisture ratio decreases continuously with drying time. No constant rate period, only falling rate period was observed throughout the experiments. Drying time decreased as power was increased. Stability reached soon when the power was high. Several authors reported that increase in temperature increases the rate [21]. Fig 2 implies the drying rate versus moisture content, drying rate was high for higher moisture content and Fig 3 showed that drying rate decreases as the drying time increases. The drying curves were fitted to various drying model and the drying model suitable for black pepper was Midilli *et al* model, due to its highest R^2 value and lowest $\chi 2$, RMSE values [22]. The R^2 varied between 0.9973 to 0.9993, $\chi 2$ ranged from 0.005808 to 0.001311 and RMSE ranged between 0.009738 to 0.02091. The statistical results of black pepper were presented in table 2. In Fig 4, the experimental data and predicted data by using Midilli *et al* model was plotted and compared.

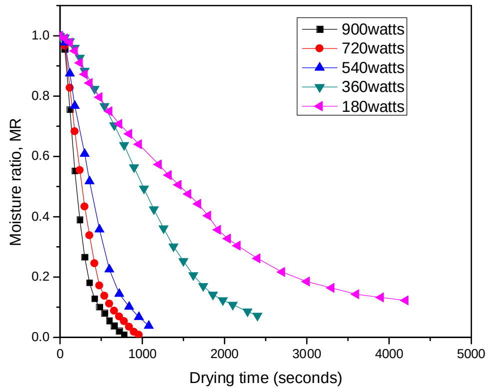

Fig. 1 Moisture ratio versus time at 900W, 720W, 540W, 360W and 180W microwave power.

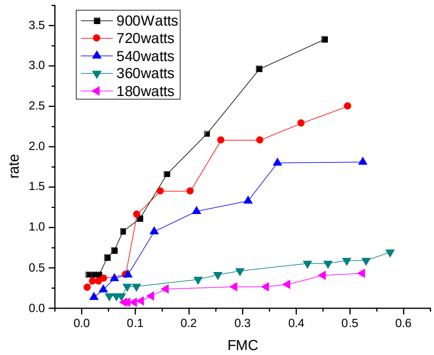

Fig. 2 Drying rate versus FMC at 900W,720W,540W,360W and 180W for microwave thin layer drying of black pepper.

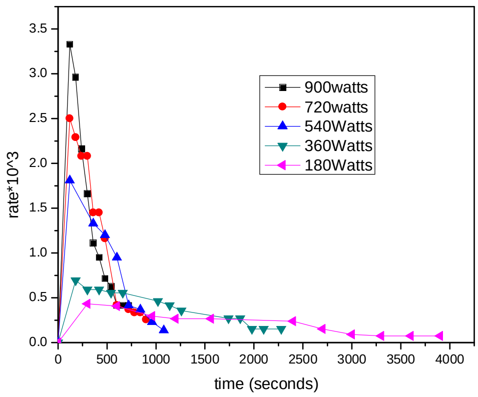

Fig. 3 Drying rate versus drying time at 900W, 720W,540W,360W and 180W for microwave thin layer drying of black pepper.

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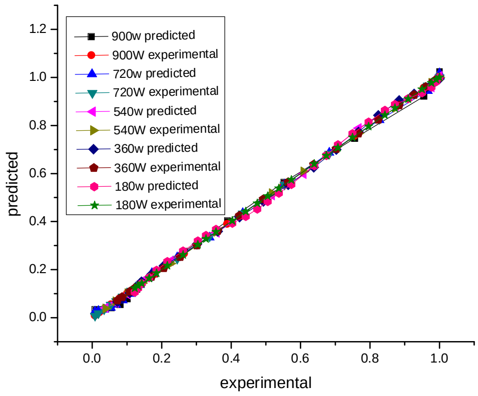

Fig. 4 Experimental versus predicted moisture ratios at 900W,720W,540W,360W and 180W by Midilli *et al* model .

Table 2 Statistical parameters for black pepper

Model	Powers	R2	RMSE	χ2
Newton	900watts	0.9582	0.07211	0.0676
	720watts	0.9606	0.06833	0.0747
	540watts	0.962	0.0714	0.05608
	360watts	0.9467	0.07931	0.1384
	180watts	0.9936	0.02377	0.01525
Page	900watts	0.9951	0.02571	0.007931
	720watts	0.998	0.01581	0.00375
	540watts	0.999	0.0123	0.001513
	360watts	0.9992	0.0099	0.002058
	180watts	0.9973	0.01571	0.006414
Modified Page	900watts	0.9547	0.07506	0.0676
	720watts	0.9606	0.07057	0.0747
	540watts	0.962	0.07489	0.05608
	360watts	0.9467	0.08118	0.1384
	180watts	0.9936	0.02422	0.01525
Henderson and pabis	900watts	0.9723	0.06107	0.04475
	720watts	0.9761	0.05492	0.04525
	540watts	0.9773	0.05791	0.03353
	360watts	0.9695	0.06142	0.07921
	180watts	0.9962	0.01877	0.009156
Logarithmic	900watts	0.9797	0.0546	0.0328
	720watts	0.9862	0.04327	0.02622
	540watts	0.9908	0.03881	0.01356
	360watts	0.9909	0.03445	0.02373
	180watts	0.9967	0.01768	0.007811
Two term	900watts	0.9693	0.07047	0.04967
	720watts	0.994	0.02957	0.01137

	540watts	0.9773	0.06104	0.03352
	360watts	0.9695	0.06293	0.07921
	180watts	0.9962	0.01914	0.009156
Two term exponential	900watts	0.9581	0.07507	0.06763
	720watts	0.9605	0.07059	0.07474
	540watts	0.9619	0.07491	0.05611
	360watts	0.9467	0.0812	0.1384
	180watts	0.9936	0.02427	0.01532
Wang and singh	900watts	0.981	0.05053	0.03064
	720watts	0.9872	0.04015	0.02418
	540watts	0.9898	0.03869	0.01497
	360watts	0.9858	0.04186	0.03679
	180watts	0.9982	0.01288	0.004311
Diffusion approximation	900watts	0.9582	0.07839	0.0676
	720watts	0.9995	0.008623	0.001041
	540watts	0.9767	0.06182	0.0344
	360watts	0.9978	0.01674	0.005601
	180watts	0.9936	0.02472	0.01527
Verma et al	900watts	0.9972	0.02021	0.004495
	720watts	0.994	0.0285	0.01137
	540watts	0.9904	0.0396	0.01411
	360watts	0.9763	0.05544	0.06148
	180watts	0.9967	0.01775	0.007878
Modified Henderson & Pabis	900watts	0.9972	0.02371	0.004498
	720watts	0.9761	0.059	0.04525
	540watts	0.9753	0.07798	0.3648
	360watts	0.9695	0.06457	0.07921
	180watts	0.9962	0.01953	0.009156
Midilli et al	**900watts**	**0.9973**	**0.02091**	**0.004372**
	720watts	**0.9988**	**0.01313**	**0.00224**
	540watts	**0.9991**	**0.0128**	**0.001311**
	360watts	**0.9993**	**0.009738**	**0.001802**
	180watts	**0.9976**	**0.01556**	**0.005808**

3.2 Calculation of effective diffusivity

The solution of Fick's second law is the most widely used theoretical model in thin layer drying of foods. The general series solution of fick's law in spherical coordinates was given below, Eq (4) in which constant moisture diffusivity, spherical samples and no shrinkage during drying was assumed [23].

$$\frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 D_{eff}t}{r^2}\right) \quad (4)$$

For long drying times, eq (4) can be simplified to a straight line equation as

$$\ln\left(\frac{M - M_e}{M_0 - M_e}\right) = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff} t}{r^2}\right) \quad (5)$$

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

The effective diffusivities were determined using the method of slopes. Effective diffusivities are typically determined by plotting experimental drying data in terms of ln(MR) versus time. From Eq. (5), a plot of ln(MR) versus time gives a straight line with a slope (k1) of:[24].

$$k_1 = \frac{\pi^2 D_{eff}}{r^2} \quad (7)$$

3.3 Calculation of Mass Transfer coefficient and Mass Biot number

Since drying involves simultaneous heat and mass transfer, for clear understanding of the process it is required to estimate the parameters governing these two transfer processes. Hence, the equimolar counter current mass transfer coefficient (k_c) and the mass biot number (B_{im}) were estimated using the standard equations represented by eq (8) and eq (9) respectively.

$$-\frac{dM}{dt} = k_c A (M - M_e) \quad (8)$$

where, $\frac{dM}{dt}$ = rate of drying and A is the area of the drying surface.

$$\text{Biot number} = \frac{k_c L}{D} \quad (9)$$

where L is the characteristic dimension which
for sphere, L = r /3 , r is the radius.
for slab, L =H, Half thickness
D is the diffusivity.

Table 3 Mass transfer parameters for Black pepper.

Microwave output Power, (W)	Diffusivity,D (m^2/s)	Mass transfer coefficient ,K_c, (m/s)	Biot number, Bi
900	4.575×10^{-9}	8.47	$20.7*10^5$
720	3.4314×10^{-9}	6.083	$19.8*10^5$
540	2.2876×10^{-9}	4.255	$20.8*10^5$
360	2.287×10^{-10}	1.284	$62.8*10^5$
180	1.1438×10^{-10}	0.863	$84.5*10^5$

The results of mass transfer parameters were presented in Table 3. Effective diffusivity increases as microwave power increases. The effective diffusivity ranged between 4.575×10^{-9} m^2/s to $1.1438\times10^{-10} m^2/s$. A similar effect was found in the air drying of grapes [25]. Mass transfer coefficient also increases with increasing microwave power. Mass Biot number decreases with the increasing microwave power.

4. Conclusions

Thin layer drying of black pepper using microwave was studied. From the experimental data, the best fit model was Midilli *et al* model, which satisfies the experimental data to a great extent. Drying curves showed that for higher powers the drying time was shorter and the drying rates were high for higher moisture content. The mass transfer coefficients varied between 0.863 to 8.47 m/s. Mass Biot numbers were found to decrease with the increasing microwave power. Effective diffusivities of black pepper were based on analytical solution of Fick's second law, which ranged between 1.1438x 10^{-10} to 4.575×10^{-9} m^2/s.

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