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Research Article

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Mathematical Modeling and Simulation of Microwave Drying Process of Papaya (*Carica papaya L.*) using MATLAB

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ABSTRACT

In this study drying characteristics of papaya (Carica papaya L.) were investigated to study the influence of microwave power, effective moisture diffusivity and geometry on drying rate. Experiments were carried out using a household microwave oven (Kenstar KK23SSL2). Papaya (Carica papaya L.) samples were cut into three geometries (cylindrical, conical and cuboidal) and were subjected to 800 W, 640 W, 480 W and 320 W microwave power. Henderson and Pabis model equation for drying was used for fitting the experimental data of drying papaya (Carica papaya L.). Statistical analysis software Data Fit 9.0 was used to evaluate the goodness of fit using coefficient of determination values (R^2). For all geometries and power input, effective moisture diffusivity was calculated. The model equation was used to simulate the drying equation in MATLAB. Results revealed that Henderson and Pabis model described the drying of papaya (Carica papaya L.) very accurately. Effective moisture diffusivity values calculated were found to resonate with the values available in literature. The simulation model in MATLAB gave reasonable results meaning thereby that simulation model captured the drying behavior of papaya (Carica papaya L.) fairly good.

Keywords: Henderson and Pabis model; Microwave drying; MATLAB simulation; Mathematical modeling and papaya

INTRODUCTION

Microwave as a source of thermal energy is finding its uses in our day to day life. The largest commercial unit that employs microwave thermal energy is the Food industry. It is also being used in ceramic processing for drying, sintering, curing epoxy resins in polymer industry, besides drying of paper, forest products and textile industries. Conventional heating methods are relatively slow methods and less energy efficient when compared to microwave heating. In conventional heating methods the surface in contact with the heating medium is hottest while the inner material remains relatively less hot. This variation is not seen in microwave heating because the waves penetrate into the material and heat it from the inside thus giving a fairly uniform temperature profile. Drying is basically a technique of preservation of foods/its products which involves the removal of water, with an aim to suppress enzymatic, chemical and microbiological activities that may cause deterioration of food material [1]. Papaya (*Carica papaya L.*) is a tropical fruit which has a very fast paced demand in markets because the fruit is a source of fibers, digestive enzymes, minerals and nutrients. Papaya (*Carica papaya L.*) is a seasonal fruit and has short shelf life, therefore it is necessary to process papaya (*Carica papaya L.*) to enhance its shelf life without affecting its nutritional value and taste. Various studies have been carried out to understand the process of microwave drying on different food materials. Soybeans [2], parsley leaves [3], carrots [4], apple [5], blanched pumpkin [6], orange seeds [7], nuts and kernels [8] are some of the food materials subjected to study in the past. Every food material has a different structure hence its interaction with microwaves is different. No single model is yet available that may explain the drying behavior of all food materials. Papaya (*Carica papaya L.*) is an important and fruit in demand and its drying characteristics need to be analyzed individually.

No attempt has been made in the past regarding simulation of drying in MATLAB which can provide better insight in understanding the effects of microwaves on food material.

MATERIAL AND METHODS

Fresh papaya (*Carica papaya L.*) was bought from market in Aligarh, in June 2016 and was initially stored in a fridge before experiments were carried out. Just before the experiments, it was taken out of fridge and allowed to reach the room temperature (average room temperature of about 32.5^{o}C). Papaya (*Carica papaya L.*) was carved into three different shaped samples, cylindrical (radius = 2.25 cm, length = 2.5 cm), cuboidal (length = 2.0 cm, breadth = 2.6 cm, height = 9.4 cm) and conical (radius = 1.75 cm, height = 5.8 cm) with the help of kitchen knife and peeler. Four samples of equal dimensions for every shape were prepared.

Equipment and Procedure

Drying experiments were carried out in the laboratory of Department of Chemical Engineering, Zakir Husain College of Engineering and Technology, Aligarh Muslim University in the month of June 2016. A domestic microwave oven (Kenstar KKS23SSL2, 800 W, 23 L) was used to dry the samples. Microwave power and drying time were adjusted using the touch panel controls provided on the oven. Drying experiments were carried out at four different powers: 800 W, 640 W, 480 W and 320 W. Samples were placed inside oven at the center of a rotating turntable with a diameter of 270mm. The oven initially was set to 800 W for a period of 8 minutes. For tabulation of moisture loss periodically, the sample was taken out of oven after a span of 40 seconds to weigh and measure temperature. Weight measurement of papaya (*Carica papaya L.*) samples was carried out using Laboratory Electronic Balance 'A & D' (Model No. EK200i). It can weigh to a maximum of 200 g with a precision of 0.01 g. For temperature measurement, digital thermometer DTM-100 (Resistance Temperature Detectors or RTD) was employed which can measure temperatures upto 600^{o}C with an accuracy of ±1.5%. The drying process was stopped only after the weight of the sample became almost constant and did not change with further subjection to microwave heating. The weighing and temperature measurement of the sample were completed in a time span of less than 10 seconds.

Mathematical Modeling

For investigation of microwave drying characteristics, it is necessary to model the drying phenomena efficiently. In the present study, experimental drying values were fitted into Henderson and Pabis [9] model of drying characteristics given by:

$$\text{M.R (Moisture Ratio)} = a*\exp(-kt) = X_t/X \quad (1)$$

where k is constant of drying s^{-1}, t is drying time in seconds and a is the dimensionless pre exponential factor. Moisture content of the samples was measured and calculated using oven method. The moisture content of sample was calculated using the following equation:

$$X_t = (M_t-M_d)/M_d \quad (2)$$

where, X_t = moisture content of sample at any time t (grams of water/grams of sample); M_t = mass of fruit/vegetable sample at any time t (g); M_d= dried mass of the fruit/vegetable sample (g);

Moisture ratio values for drying experiments were calculated using the following simplified equation:

$$\text{Moisture Ratio} = X_t/X \quad (3)$$

where, X_t = moisture content at any time t (grams of water/grams of sample); X = initial moisture content (grams of water/grams of sample)

Coefficient of Determination

The mathematical modeling was carried out using Henderson and Pabis correlation. For the selected drying model, experimental drying curves were fitted using statistical data analysis software tool Data Fit 9.0. The goodness of the fit of data was evaluated by coefficient of determination or R^2 values.

Moisture Diffusivity

Drying of the most food materials occurs in the falling rate period and moisture transfer during drying is dominated by internal transfer. Fick's diffusion equation as shown in (4) and (5), for an infinite length, assuming uni-dimensional moisture transfer, no shrinkage, constant temperature, diffusivity coefficients and negligible external resistance have been widely used to describe the drying process characteristics during falling rate period for most of biological materials [10]:

$$\text{M.R (Moisture Ratio)} = a*\exp(-kt) = X_t/X \quad (4)$$

$$MR = \frac{8}{\Pi^2} \times \sum \left[\frac{1}{(2n+1)^2}\right] \times \exp\left[\frac{-(2n+1)^2 \Pi^2 D_m t}{4L^2}\right] \quad (5)$$

Where, MR = moisture ratio, X_t is moisture content at any time t (g/g), X is initial moisture content (g/g), L is the half-thickness of the pumpkin slices (m) and D_m is the moisture diffusivity. The linear solution of (5) is obtained by assuming that the first term of the series is significant. Taking natural logarithm of the above equation yields as follows:

$$\ln(Moisture\,ratio) = \left(\frac{8}{\Pi^2}\right) - \frac{\Pi^2 D_m t}{4L^2} \quad (6)$$

Moisture diffusivity (D_m) is determined by plotting natural logarithm of moisture ratio (ln MR) against time (t) too obtain a slope which gives the value of $\frac{\Pi^2 D_m t}{4L^2}$.

Simulation

The model equation was simulated in MATLAB. A MATLAB program was written which requires two input ranges, one being the value of constant a and other is that of constant k, which were required for calculation of moisture using Henderson and Pabis correlation. The different values of constants a and k were obtained at different values of time t. The values of a and k were chosen on the basis of how close a particular a and k gave moisture ratio value when compared with its mathematical moisture ratio counterpart.

RESULTS AND DISCUSSIONS

Drying Characteristics

Papaya (*Carica papaya L.*) samples of various geometries were dried at different conditions in a microwave oven. They were subjected to microwave heating till their mass changed no more. Figure 1-6 show the variation of Moisture Ratio (M.R) with time at various microwave power. The plot also shows how geometry affects the drying phenomena in terms of moisture ratio and time. The drying time achieved for different geometries varied which is also evident from drying curves. The moisture ratio decreases continuously with increasing time.

Effect of Microwave Power

The rate of drying of samples increased with increase in microwave power. However, this rate was different ford different geometries even at same microwave power. This suggests that microwave power absorptivity of papaya samples depends upon its geometry. It also implies that that the amount of microwave power emitted is not completely absorbed by samples, only some part of microwave power was absorbed which caused the heating of papaya samples from the inside. Initially drying proceeds at faster rates when moisture content of the sample is high, but slows down with increasing time, moisture ratio recedes causing slower drying rate. This finding of variation of microwave power with moisture ratio agreed with the previous study [11].

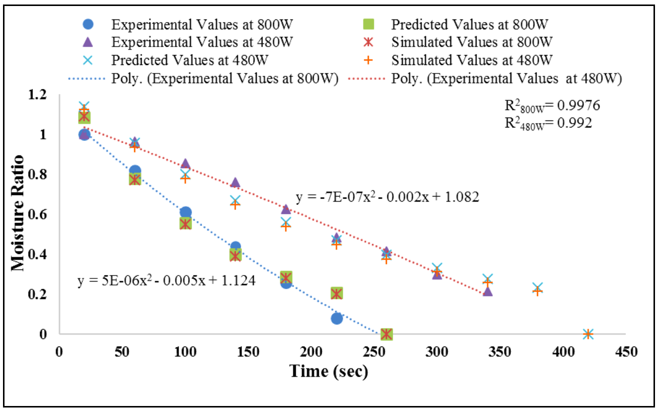

Figure 1: Drying curves for experimental, predicted and simulated values of papaya cylindrical sample at 800 W and 480 W

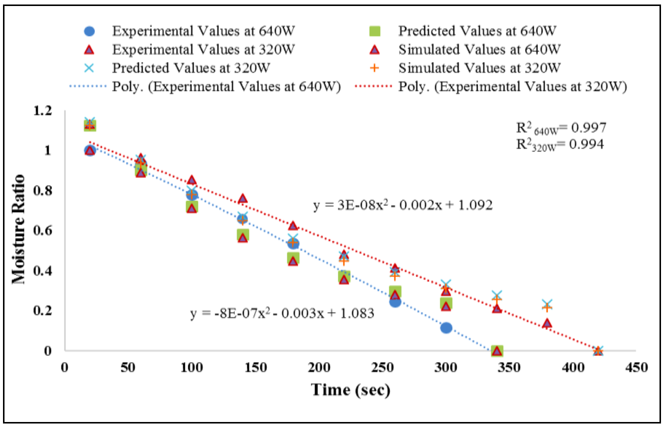

Figure 2: Drying curves for experimental, predicted and simulated values of papaya cylindrical sample at 800 W and 480 W

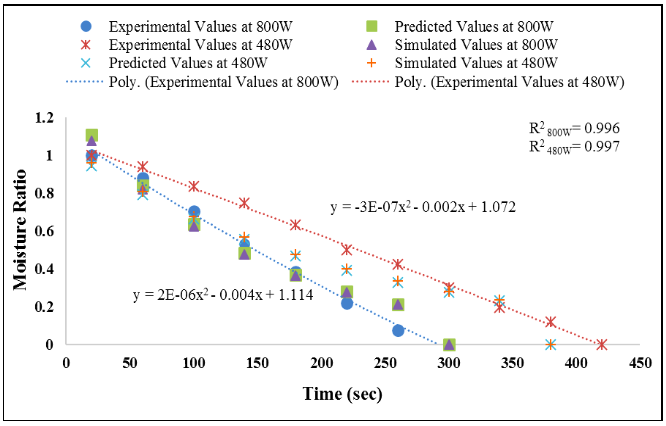

Figure 3: Drying curves for experimental, predicted and simulated values of papaya cuboidal sample at 800 W and 480 W

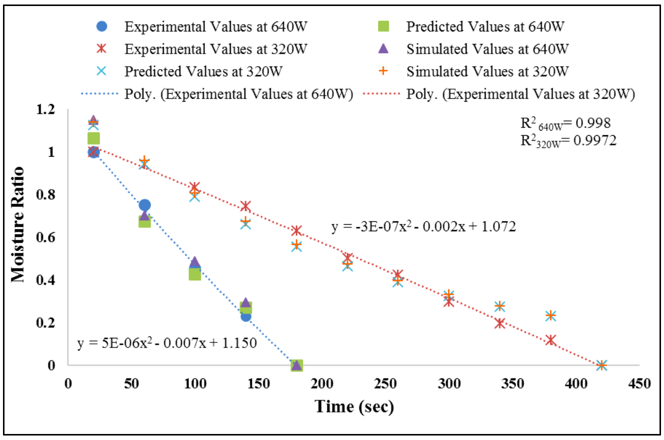

Figure 4: Drying curves for experimental, predicted and simulated values of papaya cuboidal sample at 800 W and 480 W

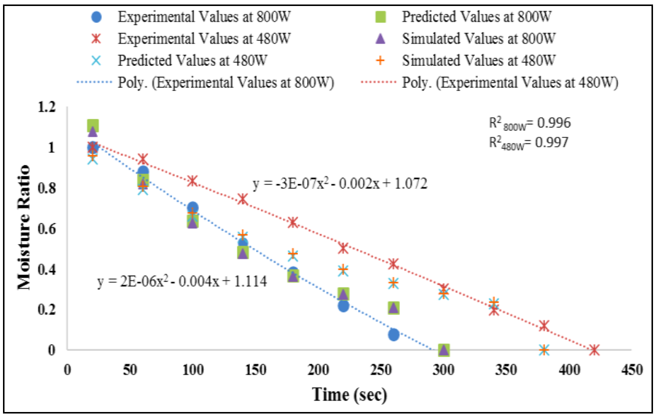

Figure 5: Drying curves for experimental, predicted and simulated values of papaya conical sample at 800 W and 480 W

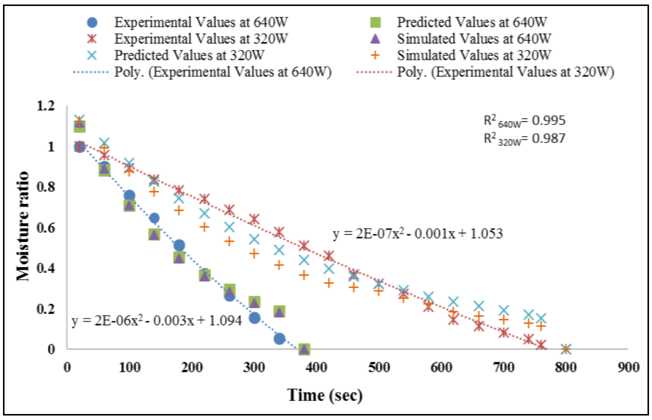

Figure 6: Drying curves for experimental, predicted and simulated values of papaya conical sample at 640 W and 320 W

Effective Moisture Diffusivity

Table 1 shows the values of effective moisture diffusivities at different drying conditions. For cylindrical geometry of papaya samples, the value of effective moisture diffusivity varied from 2.4×10^{-6} m^2/s to 5.89×10^{-5} m^2/s at different microwave input powers. Similarly for cuboidal geometry of papaya sample, the range of effective moisture diffusivity was 1.16×10^{-6} m^2/s to 2.53×10^{-5} m^2/s. At 640 W, the value of effective moisture diffusivity was highest (for cylindrical and cuboidal samples), suggesting that at this particular microwave power among all those which were studied, high rate of mass transfer was achieved which resulted in faster drying. The results indicated that values of effective moisture diffusivity were found to be higher in this study than the one conducted by Cheenkachorn et al. [11] for papaya samples using microwave vacuum drying technique. Higher value of effective moisture diffusivity means shorter drying time and faster drying rates.

Table 1: Moisture Diffusivities D_m of experimental, predicted and simulated values for different geometries of papaya

Microwave Power input	Moisture Diffusivity D_m for Cylindrical geometry, m^2/s			Moisture Diffusivity D_m for Cuboidal geometry, m^2/s		
	Exp.	Predicted	Simulated	Exp.	Predicted	Simulated
800 W	2.4×10^{-6}	1.7×10^{-6}	1.74×10^{-6}	2.04×10^{-5}	1.43×10^{-5}	7.61×10^{-6}
640 W	5.89×10^{-5}	4.35×10^{-5}	4.76×10^{-5}	2.53×10^{-5}	2.33×10^{-5}	5.12×10^{-6}
480 W	4.44×10^{-5}	3.63×10^{-5}	3.77×10^{-5}	1.16×10^{-6}	9.13×10^{-6}	9.06×10^{-6}
320 W	7.04×10^{-6}	5.18×10^{-6}	4.55×10^{-6}	7.04×10^{-6}	5.18×10^{-6}	4.55×10^{-6}

Drying Model

According to Henderson and Pabis's model of drying, the time required for drying can be calculated from equation:

$$\text{M.R (Moisture Ratio)} = a^*\exp(-kt) \quad (7)$$

Figures 1-6 show the variation of experimental, mathematically predicted and simulated relationship between moisture ratio and drying time. Table 2 gives the value of R^2 (coefficient of determination). It is evident from the values of R^2 that Henderson and Pabis's model accurately represents the experimental data for all tested drying conditions. The constant k in the model equation is a measure of drying rate, higher the value of k is, faster is the drying. At 800 W microwave power value of k is highest and lowest at 320 W. When compared at same value of microwave power, cylindrical geometry was found to have the highest value of constant k. The range of values of k at 800 W was 6.8×10^{-3} to 8.5×10^{-3} s^{-1}, at 640W the range was 5.8×10^{-3} s^{-1} to 1.02×10^{-3} s^{-1}, at 480W it was 4.6×10^{-3} s^{-1} to 3.0×10^{-3} s^{-1} and at 320W, 3.1×10^{-3} s^{-1} to 2.2×10^{-3} s^{1}.

Table 2: R^2 values for different microwave powers and geometries for papaya

S. No.	Microwave Power	R^2 values		
		Cylindrical	Cuboidal	Conical
1	800 W	0.9976	0.996	0.998
2	640 W	0.997	0.998	0.995
3	480 W	0.992	0.997	0.994
4	320 W	0.994	0/9972	0.987

Simulation

A MATLAB program was written based on Henderson and Pabis's model equation for drying. This is a first attempt of its kind of simulating a drying model equation using MATLAB. Figures 1-6 give a comparison of experimental, predicted and simulated values of moisture ratio. The values are not a 100% representation of experimental data but the MATLAB program gave accurate results to some extent. The degree of accuracy of simulated model is visible in figures shown.

CONCLUSION

Papaya (*Carica papaya L.*) samples were subjected to different drying conditions using a microwave oven. Effects of microwave power, effective moisture diffusivity and geometry were studied. Influence of microwave power was observed to follow the same trend as reported in literature. Higher value of microwave power caused faster drying and drying was achieved lesser time. The effective moisture diffusivity was calculated and was found higher than previous study. The values of coefficient of determination R^2 represents a close relationship between experimental and predicted values. The MATLAB program compiled is very flexible and is equally eligible and applicable to other drying model equations as well. There is scope in improvement in the conditions of experimentation which include modifying/designing an oven with an inbuilt temperature and mass monitoring equipment. This investigation implies that Henderson and Pabis model is the best fit model equation for papaya (*Carica papaya L.*). More experimental work and mathematical modeling is required for developing a uniform model equation that will explain the drying of all food materials.

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