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Kinetics of Parboiled Paddy under Microwave Drying

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Microwave drying provides high heating rate and rapid moisture removal. The objective of this research was to investigate the effect of bed thickness and power levels on drying kinetics and to assess the quality of parboiled paddy under microwave drying. Effect of process variables, namely microwave power (180, 360, 540 and 720 W) and bed thickness (1.5, 3, 4.5 and 6 cm) were studied on drying rate, moisture ratio, moisture diffusivity and activation energy. Drying time significantly decreased with increase in power while increased with increasing bed thickness. Drying rate curves revealed that drying occurred only in falling rate period. The drying data were fitted with several established thin layer drying models. Moisture diffusivity increased with increase in power and decreased with increase in bed thickness. The highest diffusivity of 30.8×10^{-10} m^2/s was found at 720 W and 1.5 cm thickness while the lowest diffusivity of 3.08×10^{-10} m^2/s was observed at 180 W and 6 cm thickness. The highest value of activation energy was found to be 7.718 W/g for 1.5 cm bed thickness whereas the lowest was 2.58 W/g for 6 cm bed thickness.

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Keywords: Microwave drying; drying kinetics; modeling; moisture diffusivity; activation energy.

1. INTRODUCTION

Rice (*Oryza sativa* L.) is the most important staple food in Asia. More than 90% of the world's rice is grown and consumed in Asia, which is home to 60% of the world's population. Rice accounts for 35-60% of the caloric value intake of three billion asians [1]. Paddy is normally harvested at a high moisture content of about 20% to 24% (w.b.). After harvesting to prevent deterioration, the paddy should be dried down to a safe moisture content of about 12-14% (w.b.), which is considered safe for storage, milling and further storage as milled rice [2,3]. Parboiling is the pre-milling treatment which improves the quality of rice. Parboiling process consists of three major steps- soaking, steaming and drying. Drying is the king pin parboiling process so far as the milling quality is concerned. Most conventional method used is hot air drying but it has major disadvantages which includes higher energy consumption, longer time duration and low drying efficiency [4]. In conventional drying method the heat is transferred from the source to the food surface by convection which makes drying a slow process. Contrary to this, the other efficient method of heat and mass transfer is electromagnetic radiation [5]. The microwave drying mechanism is based on the interaction between water dipolar molecules and the electromagnetic field. Thus, the higher moisture content part of a product can absorb more energy which results in faster drying [6]. The microwave power varies from 170 to 500 watts while the pulsation periods varied from 30 to 120 seconds [4]. Studies related to microwave drying of high moisture paddy at different power levels and bed thickness was not reported earlier. Hence the objective of the present work was to study the effect of microwave power levels and bed thickness on drying kinetics of parboiled paddy and to determine the effective moisture diffusivity and the activation energy of parboiled paddy under microwave drying.

2. MATERIALS AND METHODS

2.1 Preparation of Samples

IR 36 variety of paddy was procured and chaff, dirt, twigs etc. were removed by cleaning paddy in two passes through an aspirator. Complete removal of immature paddy grains and other impurities were ensured. The paddy soaked in hot water at a temperature of 70-75℃ with time of 2-2.5 hour in water bath. Pressurized (1.5 kg/cm^2) steam was passed through the perforated pipes until the husk just began to crack [7].

2.2 Drying Procedure

Each sample was spread on the microwave container at different depths of 1.5, 3, 4.5, 6 cm on the microwave oven and treatment was applied at four different power levels (180,360, 540 and 720 W). Paddy at 30% (w.b.) moisture was used in the experiments. For each series of drying tests, samples were dried at different power level and bed thickness. The moisture contents at the beginning of the drying tests were determined by the oven drying method. Different thickness samples were used in all microwaves drying test. The samples were dried individually in a microwave container forming a different layer of parboiled paddy. The sample container was placed on the microwave oven center. During drying the samples were periodically removed and weighed using a digital balance (Shimadzu TX-423L) to the nearest 0.01 g. The weighing was done at different time intervals. The samples were dried until the moisture content was 14±1% (w.b).

Fig. 1. Microwave dryer

2.3 Microwave Container

Microwave containers were purchased from the market with a capacity of 2 litre. The containers were made up of plastic and shape of the container was elliptical. The height of the container was 8 cm and the containers had holes through out having the size of 2 mm diameter. The distance between holes to hole was 4 mm.

2.4 Mathematical Modeling

Various empirical models were developed earlier for assessing the thin layer behavior. Generally it is assumed that at any instant during drying, the moisture evaporation rate varies proportionaly with change in moisture concentration of the product, this can be presented by an equation analogous to Newton's law of cooling [8] as

$$\frac{dM}{dt} = -k_d(M - M_e) \quad (1)$$

The generalized form of the above equation is:

$$\text{MR}=\frac{M-Me}{Mo-Me}=\text{exp (kt)} \quad (2)$$

Where, M is the moisture content at any time t (s), Me is the equilibrium moisture content (db), M_o is the initial moisture content (db), t is drying time (s), k_d is the drying rate constant (s^{-1}). The drying curves were obtained and processed for drying rate to find the best fit among the 6 models with a different microwave power levels (180, 360, 540 and 720 W) and bed thickness (1.5, 3, 4.5 and 6 cm). The thin layer models are listed in Table 1. The model coefficient for all the six models along with the statistical parameters was estimated by nonlinear regression technique using software ORIGINPRO 8. The statistical results of the different models, including the comparison criteria used to evaluate goodness of fit, viz., the value of coefficient of determination (R^2) and reduced chi-square (X^2) are presented. The goodness of fit of the models are characterized by the highest value of coefficient of determination (R^2) and lowest value of reduced chi-square (X^2).

2.5 Estimation of Effective Moisture Diffusivity

The drying of grains usually occurs under falling rate period. Fick's second law Eq. (1) was used to calculate the diffusivity (Crank, 1975)

$$\frac{\partial M}{\partial t} = D[\frac{\partial^2 M}{\partial r^2} + \frac{2}{r}\frac{\partial M}{\partial r}] \quad (3)$$

Where M is moisture content (db.), D is moisture diffusivity (m^2/s) and r is the radius of a small sphere (m) from which moisture is diffusing. For simplified the above equation we assumed that Paddy has a spherical shape with radius, r; during drying Moisture Diffusion is homogeneous throughout the rice kernel; Moisture migration takes place radically outwards from inside the grain; Shrinkage of the rice kernel during drying is negligible; and Mass transfer is symmetric and resistance to mass transfer at the surface of kernel is negligible. These assumptions were incorporated to the eq. (1) [15,16,17].

$$MR = \frac{M-Me}{M_0-Me} = \frac{6}{\pi^2}\exp\left(-\frac{\pi^2 \times D \times t}{r^2}\right) \quad (4)$$

$$MR = \frac{M}{M_0} = \frac{6}{\pi^2}\exp\left(-\frac{\pi^2 \times D \times t}{r^2}\right) \quad (5)$$

$$LN(MR) = LN\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 \times D}{r^2}\right)t \quad (6)$$

Where MR is moisture ratio, M_o is initial moisture content (db.), M is moisture content at a given time (db.), M_e is equilibrium moisture content (db). Many researchers found that under higher heating, average exposure time (t) and the equilibrium moisture content M_e was zero [15,18]. Diffusivity is determined by plotting the ln (MR) versus drying time t in equation (4), the plot gives a straight line with a slop of ($\frac{\pi^2 \times D}{r^2}$).

Table 1. Model for predicting microwave drying characteristics of paddy

Model name	Model equation	Reference
Lewis	MR=exp (-kt)	Lewis (1921) [9]
Page	$MR = \exp(-kt^n)$	Karathmos et al. (1999) [10]
Modified page	$MR = \exp(-(kt)^n)$	White at al.(1981) [11]
Handerson and Pabis	$MR = a\exp(-kt)$	Akpinar at al. (2003) [12]
Logarthamic	$MR = a\exp(-kt) + c$	Yaldiz et al. (2001) [13]
Two terms exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Togarul et al. (2003) [14]

3. RESULTS AND DISCUSSION

3.1 Effect of Process Variable on Drying Time

Drying of parboiled paddy under microwave drying from 42.86 to 14.1 % ±1 (d.b) moisture content was carried under different drying conditions. The variation in moisture content with elapsed drying time at each of the bed thickness values are shown in Fig. 1. The drying time increased appreciably as the bed thickness increased from 1.5 to 6 cm. The drying time decreased with increase in power level from 180 to 720 W due to increase in the water vapour pressure within the sample which increased the migration of moisture from inside of the product to its surface. Similar finding were reported by some authors (Y. Soysal, 2004; I. Alibas Ozkan, 2007: K. Cheenkachorn, 2007: Songul Gursoy, 2013) The time required for drying the parboiled paddy up to 14±1% (d.b) takes 5.5 Min for 1.5 cm thickness with 720 W microwave power and 68 min for 6 cm bed thickness at 180 W microwave power. As expected higher the microwave power, higher would be the mass transfer which results in higher drying rate and consequently lower drying time.

3.2 Effect of Process Variable on Drying Rate

The variation of the drying rates against drying time at different microwave power levels were observed with different thickness as shown in Fig. 2. For a grain bed depth of 1.5 cm the drying rate increased rapidly in the beginning, attained a maximum value at about 6 min followed by a gradual decrease. The average drying rate varies from 3.19 to 0.17 (kg of water/ kg of dry solid). Min^{-1}. The drying rate increased with increase in microwave power while decrease in

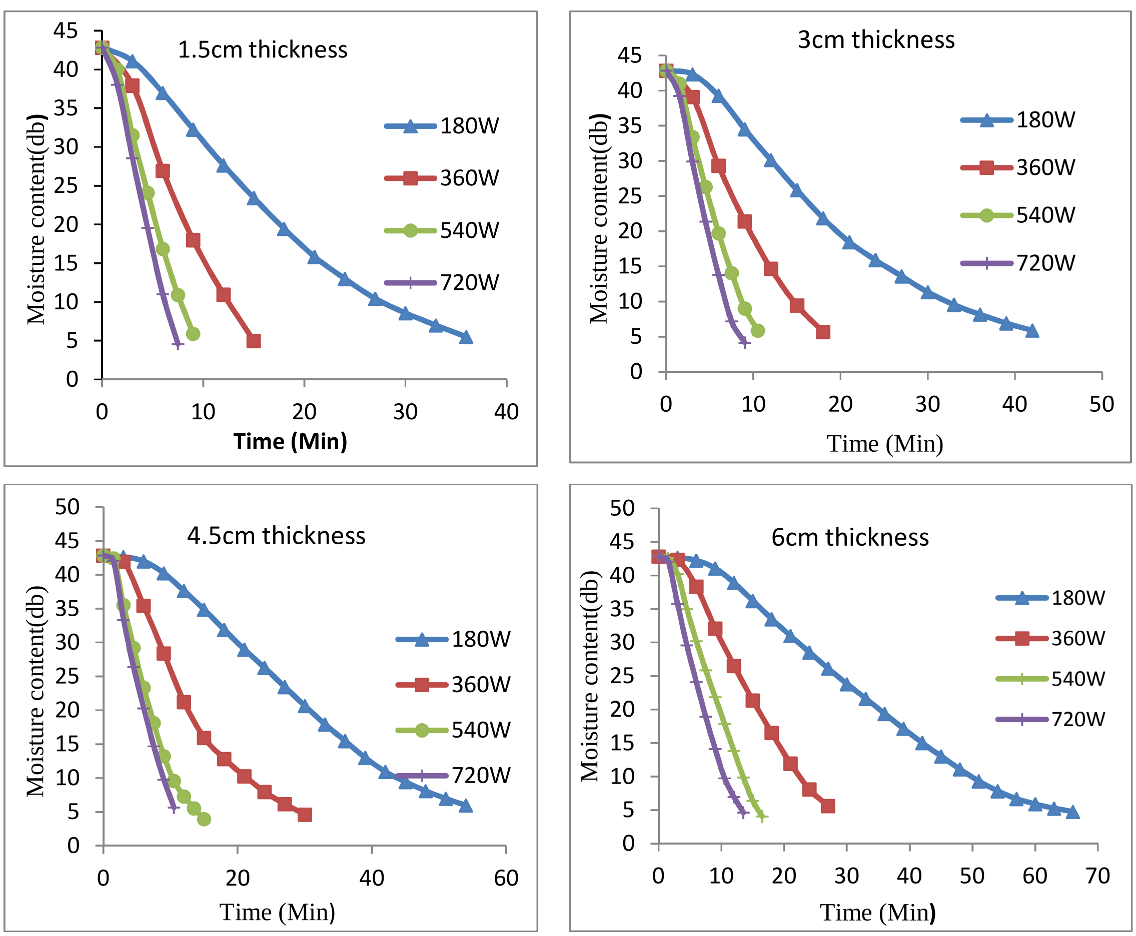

Fig. 1. Relationship between the moisture content (kg of water/ kg of dry matter) and drying time (Min) at different bed thickness (1.5, 3. 4.5 and 6 cm) and microwave power (180, 360, 540 and 720 W)

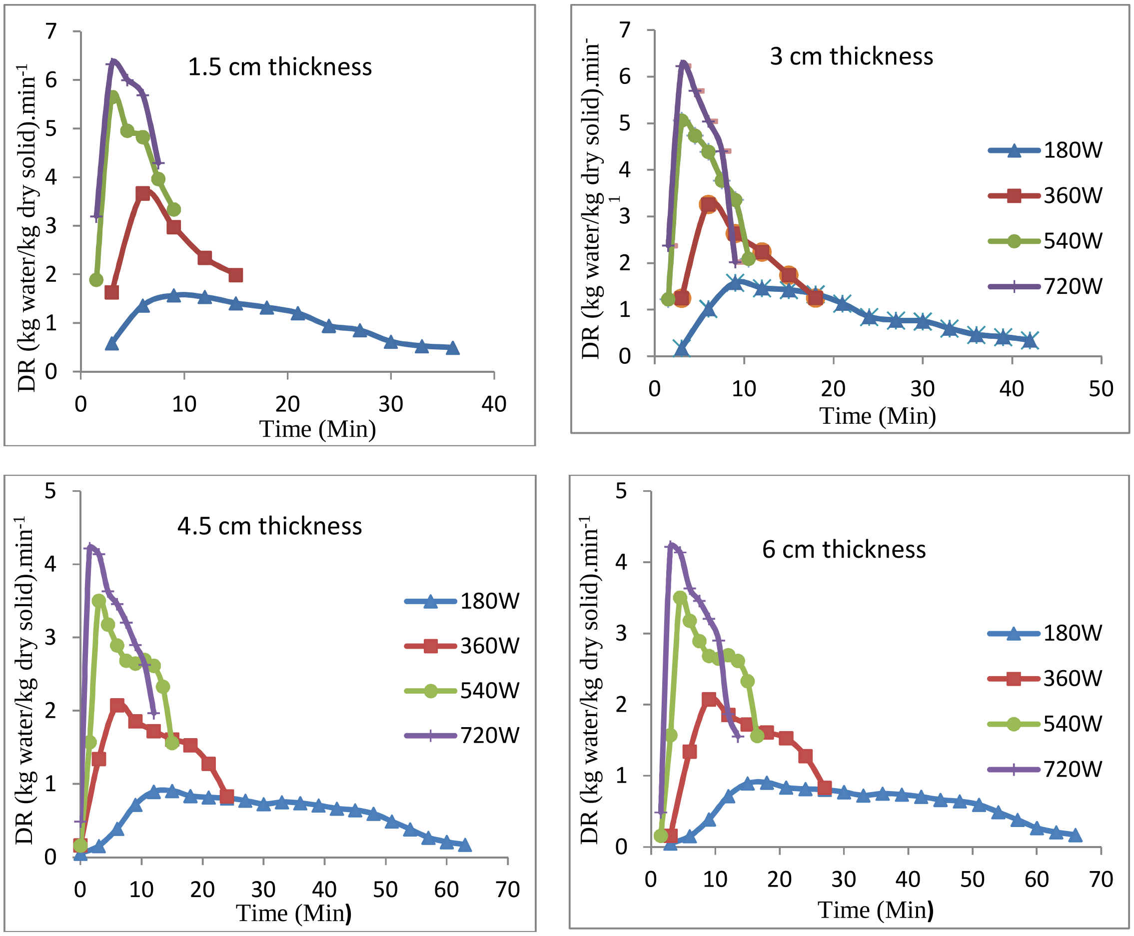

Fig. 2. Relationship between the drying rate (kg water/kg dry solid).min^{-1}and drying time (min) at different bed thickness (1.5, 3. 4.5, 6 cm) and microwave power (180, 360, 540, 720 W)

bed thickness. Two drying periods were observed, namely, an initial warm up period during which increase in drying rate took place and followed by a falling rate period characterized by a decrease in drying rate. No constant rate period was observed in all these drying conditions. Same trend was reported previously [16].

The moisture content of parboiled paddy was higher during the initial part of drying and this high moisture content was responsible for higher microwave power absorption, which might have caused a higher rate of heating and higher drying rate. The loss of moisture in the parboiled paddy reduced the absorption of microwave power which resulted in the decrease in drying rate. Thus, higher the microwave power output higher the drying rate. Similar finding were found in previous study [1,19,20,21].

3.3 Modeling of Drying Characteristics

The moisture ratio (MR) was simplified to M_t /M_o instead of (M_t-M_e) / (M_o-M_e). The experimentally observed value of M_t and Mo were used to analyze the change in moisture ratio respect to time for various operational conditions. The MR versus time data was fitted to the selected thin layer drying models mentioned in Tables 2 to 5. The model coefficients for all the six models along with the statistical parameters were estimated by nonlinear regression technique using software ORIGINPRO 8. The statistical results of the different models, including the comparison criteria used to evaluate goodness of fit, viz., the value of coefficient of determination (R^2) and reduced chi-square (X^2) are presented in Tables 2 to 5. The goodness of fit of the models characterized by the highest value of coefficient of determination (R^2) and lowest value of reduced chi-square (X^2).

Table 2. Statistical results obtained from various thin layers drying models for 1.5 cm of bed thickness

Model	Power (W)	Chi-square (X^2)	R^2	Variables
Page	180	5.37111×10^{-5}	0.99953	k=0.01149,n=1.45861
	360	9.69269×10^{-5}	0.99929	k=0.02242,n=1.66458
	540	1.55736×10^{-4}	0.99882	k=0.04702,n=1.66944
	720	1.0762×10^{-4}	0.99926	k=0.05461,n =1.79887
Modified page	180	5.37112×10^{-5}	0.99953	k=0.04678,n =1.45854
	360	9.69129×10^{-5}	0.99929	k=0.10214,n =1.66333
	540	1.55698×10^{-4}	0.99882	k=0.16021,n =1.66741
	720	1.07624×10^{-4}	0.99926	k=0.19863,n=1.79929
Two terms exponential	180	1.00434×10^{-4}	0.96167	k=0.04834,a=0.99874
	360	2.83776×10^{-4}	0.99792	k=0.1787,a=2.15714
	540	2.71876×10^{-4}	0.99793	k=0.27938,a=2.15366
	720	9.34827×10^{-4}	0.99359	k=0.35283,a=2.19245

Table 3. Statistical results obtained from various thin layers drying models for 3 cm of bed thickness

Model	Power (W)	Chi-square (X^2)	R^2	Variables
Page	180	3.12394×10^{-4}	0.9971	k=0.01117,n =1.39737
	360	9.5478×10^{-5}	0.99926	k=0.02055,n=1.59393
	540	2.07959×10^{-4}	0.99821	k=0.0416,n=1.6286
	720	7.18739×10^{-5}	0.99949	k=0.0502,n=1.74947
Modified page	180	3.12394×10^{-4}	0.9971	k=0.0401,n=1.3956
	360	9.5478×10^{-5}	0.99926	k=0.0874,n=1.59398
	540	2.07959×10^{-4}	0.99821	k=0.0141,n=1.62543
	720	7.18739×10^{-5}	0.99949	k=0.1710,n=1.7488
Two terms exponential	180	9.13932×10^{-5}	0.99915	k=0.06506, a=2.00596
	360	2.43397×10^{-4}	0.99813	k=0.15039, a=2.11753
	540	1.0355×10^{-4}	0.99912	k=0.24623, a=2.14404
	720	5.04244×10^{-4}	0.99644	k=0.32099, a=2.18903

Table 4. Statistical results obtained from various thin layers drying models for 4.5 cm of bed thickness

Model	Power (W)	Chi-square (X^2)	R^2	Variables
Page	180	1.74379×10^{-4}	0.99852	k=0.0019,n=1.74634
	360	5.82875×10^{-4}	0.9949	k=0.01732,n=1.45065
	540	3.10179×10^{-4}	0.99761	k=0.03182,n=1.71
	720	4.36054×10^{-4}	0.99685	k=0.02,n=1.9887
Modified page	180	1.74379×10^{-4}	0.99852	k=0.02766,n=1.73796
	360	5.82875×10^{-4}	0.9949	k=0.06107,n=1.44226
	540	3.10179×10^{-4}	0.99761	k=0.13317,n=1.7106
	720	4.36054×10^{-4}	0.99685	k=0.13985,n=1.98461
Two terms exponential	180	2.83657×10^{-4}	0.99759	k=0.04846,a=2.17764
	360	1.89775×10^{-4}	0.99834	k=0.1028,a=2.07591
	540	6.50182×10^{-4}	0.99499	k=0.23553,a=2.17531
	720	9.24872×10^{-4}	0.99333	k=0.25435,a=2.27261

Table 5. Statistical results obtained from various thin layers drying models for 6 cm of bed thickness

Model	Power (W)	Chi-square (X^2)	R^2	Variables
Page	180	3.40856×10^{-4}	0.99705	k=0.00178,n=1.70344
	360	8.3643×10^{-5}	0.99939	k=0.00479,n=1.83744
	540	1.76793×10^{-4}	0.99871	k=0.01031,n=1.91201
	720	1.18699×10^{-4}	0.99904	k=0.02816,n=1.6775
Modified page	180	3.39603×10^{-4}	0.99705	k=0.02432,n=1.69228
	360	8.3642×10^{-5}	0.99939	k=0.05466,n=1.83704
	540	1.76775×10^{-4}	0.99871	k=0.09141,n=1.91363
	720	1.18684×10^{-4}	0.99904	k=0.11966,n=1.67613
Two terms exponential	180	2.9839×10^{-4}	0.99741	k=0.04236,a=2.16195
	360	0.00121	0.99115	k=0.16519,a=2.2349
	540	6.94278×10^{-4}	0.99493	k=0.09836,a=2.2244
	720	2.62872×10^{-4}	0.99788	k=0.20829,a=2.15781

The value of coefficient of determination (R^2) as evident from the above tables, varied from 0.93865 to 0.99953 for 1.5 cm, 0.94153 to 0.99949 for 3 cm, 0.92405 to 0.99852 for 4.5 cm and 0.91786 to 0.99939 for 6 cm thickness, whereas the chi-square were found to be varying from 5.37112×10^{-5} to 0.00894 for 1.5 cm, 7.18739×10^{-5} to 0.00827 for 3 cm, 1.74379×10^{-4} to 0.00909 for 4.5 cm and 8.3642×10^{-5} to 0.00821 for 6 cm thickness. The models describing the best thin layer drying characteristics is the Page and Modified Page models, yielding the highest R^2 and the lowest χ^2 for the all different bed thickness and power levels. The second best fitted models were found to be the two terms exponential model for all different thickness and power levels.

3.4 Effective Moisture Diffusivity and Activation Energy

3.4.1 Calculation of the effective moisture diffusivity

To calculate the effective moisture diffusivity by using the method of slopes, the logarithm of moisture ratio values, ln(MR), were plotted against drying time (t) in accordance to the experimental data obtained at various microwave output powers (180, 360, 540 and 720 W) and bed thickness(1.5, 3, 4.5 and 6 cm). The linearity of the relationship between ln(MR) and drying time (t) was observed for various microwave output powers and bed thickness.

The effective moisture diffusivity values (D_{eff}) and the corresponding values of coefficients of determination (R^2) of Eq. (5) were presented in Table 6 for various microwave output powers and for various bed thicknesses. Drying occurs under falling rate period. Ipsita Das [22] studied effective moisture diffusion for high moisture paddy under infrared drying which ranged between the 0.778×10^{-10} and 3.884×10^{-10} m^2/s for different drying treatments. Khir [15] observed that High heating rate and moisture diffusivity could be achieved with IR heating. It took only 60, 90 and 120 s to achieve about 60℃ temperature with corresponding moisture diffusivities of 4.8×10^{-9}, 3.6×10^{-9} and 3.4×10^{-9} m^2/s during heating for drying bed thicknesses of a single layer, 5 mm and 10 mm, respectively.

The effective moisture diffusivity of paddy for microwave drying at 180 W decreased from 4.23×10^{-10} to 3.08×10^{-10} m^2/s, at 360 W decreased from 13.86×10^{-10} to 3.85×10^{-10} m^2/s, 540 W decreased from 20.03×10^{-10} to 13.09×10^{-10} m^2/s and 720 W decreased from 30.81×10^{-10} to 14.25×10^{-10} m^2/s, as the bed thickness increased from 1.5 cm to 6 cm for all drying condition. As the power increased moisture diffusivity also increased. Same results was obtained previously before [23,24] at the same time increasing bed thickness decreased the moisture diffusivity as shown in Table 6. This may be because, the increase in electromagnetic radiation caused rapid rise in temperature of the product, which increased the vapour pressure and consequently led to faster drying diffusion of moisture towards the surface. (D_{eff}) average decreased with increase in bed depth. The resistance to the moisture movement may be more in case of higher bed thickness, which resulted in decrease in effective moisture diffusivity [22].

3.4.2 Estimation activation energy

In this study the temperature could not be directly measured in the microwave oven used for drying.

For the calculation of activation energy the Arrhenius equation was modified to illustrate the relationship between kinetic rate constant and the ratio of the microwave output power to sample amount instead of the temperature. The drying rate constant is calculated be using best fit model.

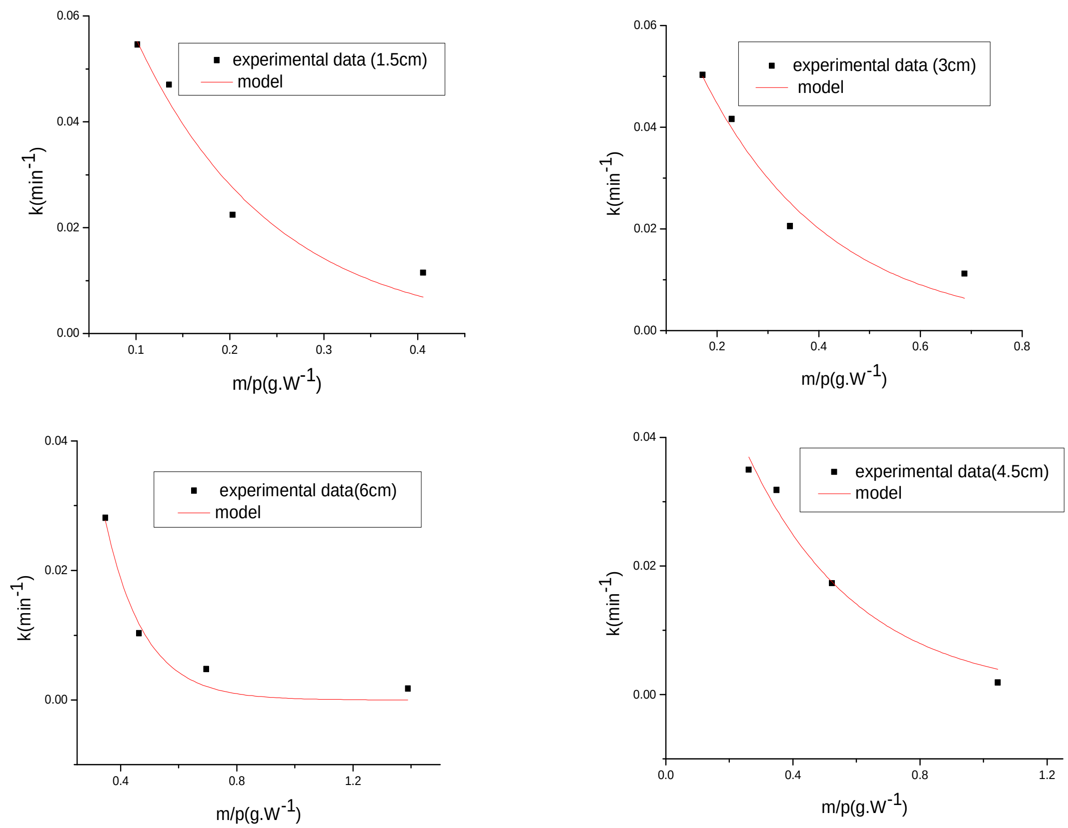

Fig. 3. Relationship between the values of drying rate constant and power

Table 6. The estimated effective moisture diffusivity and statistical analysis of linear model at various microwave output powers for different bed thickness

Thickness (cm)	Power (W)	Slope	D_{eff} ($10^{-10}m^2/s$)	R^2
1.5	180	0.0011	4.237143	0.9994
	360	0.0036	13.86701	0.9831
	540	0.0052	20.03013	0.9845
	720	0.008	30.81558	0.9856
3	180	0.0009	3.466753	0.9998
	360	0.0025	9.629869	0.9956
	540	0.0045	17.33376	0.9967
	720	0.0062	23.88208	0.9948
4.5	180	0.0009	3.466753	0.9991
	360	0.0014	5.392727	0.9982
	540	0.0033	12.71143	0.9991
	720	0.0047	18.10415	0.9861
6	180	0.0008	3.081558	0.9994
	360	0.001	3.851948	0.9942
	540	0.0034	13.09662	0.9666
	720	0.0037	14.25221	0.9933

$$K = k_{o} \times \exp\left(\frac{-E_a . m}{P}\right) \quad (7)$$

Where, K is the drying rate constant (min^{-1}), k_o is the pre-exponential constant (min^{-1}), E_a is the activation energy (W /g), P is microwave output power (W) and m is the mass of raw sample (g).The values of k versus m/ P are shown in Fig. 3. The values of k_o and E_a are shown in Table 7. As the bed thickness increases the activation energy decreases from 6.83751 to 1.0385 W/g.

3.4.3 Effect of ratio of microwave output power to sample amount on effective moisture diffusivity

The aim of this study was to predict a relationship between the effective moisture diffusivity and the ratio of microwave output power to sample amount by following the procedure as mentioned in the previous section. After evaluation of the data, the dependence of the effective moisture diffusivity on the ratio of microwave output power to sample amountwas determined, Arrhenius type exponential model, which was derived [25,26] as show in equation (8).

$$D_{eff} = D_o \exp\left(\frac{-Ea.m}{P}\right) \quad (8)$$

Where P is the microwave output power (W), m is the weight of sample (g), D_{eff} is the effective moisture diffusivity (m^2s^{-1}); D_o is the pre-exponential factor (m^2s^{-1}) and E_a is the activation energy (W /g) the fitness of the data with the model is illustrated in Fig. 4. The values of D_o and E_a are shown in Table 8. As a conclusion, the value of E_a found from this study was almost near to the value obtained from the previous section 3.4.2.

Table 7. Relationship between activation energy and sample amount/power

Thickness (cm)	k_o	E_a (W/g)	R^2
1.5	0.11039	6.83751	0.92891
3	0.09941	4.0067	0.92754
4.5	0.07789	2.8518	0.96298
6	0.05523	1.03815	0.95493

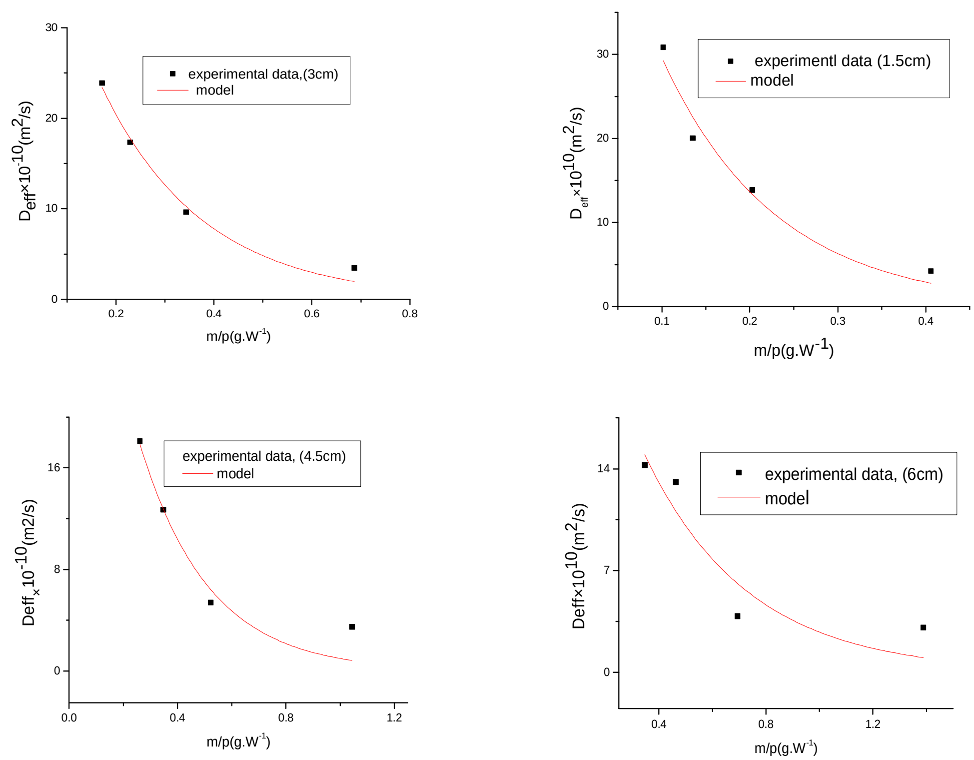

Fig. 4. Relationship between effective moisture diffusivity and power

Table 8. The estimated activation energy, moisture diffusivity coefficient, D_o (m^2 /s) and statistical analysis for various bed thickness

Thickness (cm)	D_o ($10^{-10}m^2/s$)	E_a(W/g)	R^2
1.5	63.994	7.7181	0.9555
3	53.48436	4.8129	0.98073
4.5	49.7183	3.91845	0.9159
6	36.72391	2.58529	0.8025

4. CONCLUSIONS

Drying time was significantly decreased with increase in microwave power levels while it showed an increase with increasing bed thickness. For bed thickness of 6 cm and 180 W power levels moisture level reduced up to 14% and took the time of 45 min. The lowest drying time of 5 minutes was observed with bed thickness of 1 cm and Microwave power level of 720 W. Drying rate curves revealed the presence of a falling rate period for all the drying conditions. As microwave power increased the drying rate also increased for all drying conditions. On the contrary, an increase in bed thickness caused a reduction in drying rate. The average drying rate varies from 3.19 to 0.17 (kg of water/ kg of dry solid). Min^{-1}. Highest drying rate was found at 1.5 cm bed thickness and 720 W while lowest found at 6cm bed thickness and 180 W of microwave power. Dimensionless moisture contents or moisture ratios were plotted with time using thin layer empirical models viz., Lewis, Page, Modified Page, Handerson and Pabis, logarithmic and two term exponential models. Page and Modified Page model were in good agreement between experimental and predicted moisture ratio values depicting higher coefficients of determination and lower standard error of estimation. The value of the drying rate constant (k), increased with increase in microwave output power, on the other hand, decreased with the increase in bed thickness. Moisture diffusivity increased with increasing microwave power level and decreased with increase in bed thickness. The highest diffusivity found at 720 W and 1.5 cm thickness was 3.08×10^{-10} m^2/s while the lowest diffusivity of 3.08×10^{-10} m^2/s was observed at 180 W and 6 cm thickness. The activation energy of paddy was calculated by using the exponential expression based on Arrhenius equation. Activation energy decreased with increase in bed thickness. The highest value of activation energy was found to be 7.718 W/g for 1.5 cm bed thickness where as the lowest was 2.58 W/g for 6 cm bed thickness.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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