Mathematical modeling of microwave drying of crashed cotton stalks for man-made composite material

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Abstract: Drying characteristics, energy consumption and drying kinetics modeling of crashed cotton stalks dried in a microwave dryer were investigated in this research. A microwave dryer with an output power of 1000 W and 2450 MHz was employed, and the effects of material load ranging from 50 g to 250 g on drying time, drying rate, drying efficiency and specific energy consumption were evaluated. The results showed that drying rate decreased with drying duration. A rising rate period was followed by a falling rate period and the overall drying process occurred in the falling rate period. Six mathematical models were used to fit the drying rates data of crashed cotton stalks, and Midilli et al. model was found the best prediction model by comparing R^2, *RMSE* and χ^2 values between experimental and predicted moisture ratios. With decrease in material load from 250 g to 50 g, effective moisture diffusivity increased from 2.8668×10^{-8} m^2/s to 7.9817×10^{-8} m^2/s. Results also indicated that drying efficiency and specific energy consumption significantly increased with the increase of the material load. Average drying efficiency and specific energy consumption varied in the range of 7.52%-19.78% and 12.49-35.90 MJ/kg water, respectively. There were a lowest energy consumption of 10.99 MJ/kg water and a highest drying efficiency of 17.13% at the material load level of 250 g.

Keywords: mathematical modeling, crashed cotton stalks, man-made composite material, microwave drying, kinetics
DOI: 10.3965/j.ijabe.20160902.2190

Citation: Wang H T, Li P, Guo K Q. Mathematical modeling of microwave drying of crashed cotton stalks for man-made composite material. Int J Agric & Biol Eng, 2016; 9(2): 171－178.

1 Introduction

Crop straw is a kind of renewable resource, and its main component is similar to part of the broadleaf timber[1,2]. Cotton stalk is mainly composed of cellulose, hemicellulose and lignin, which is a good straw biomass resources of alternative to wood resources[3]. Reconstituted square lumber made from cotton stalk is a new type of man-made composite material and has a promising future, which is a new trend of material utilization of cotton stalk. Its preparation process mainly includes cotton stalk extruding, drying, glue blending, lay-up, pressing in four surfaces, and after-treatment[4]. The initial moisture content of crashed cotton stalk is usually over 100% (dry base, db), but according to requirement of process, the final moisture content should not exceed 6%[5]. Therefore, drying is essential for the production of crashed cotton stalk after retting process, which directly affects the production efficiency and performance of reconstituted square lumber.

Drying means a removal of water from materials, which not only affects water content of the product but

Received date: 2015-10-18 **Accepted date:** 2016-03-01
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also alters other physical and chemical properties, such as reconstitute square lumber machining properties of planning, mortising and turning[6]. Commonly, natural crop straws are dried under sunlight and hot air. But these methods have some disadvantages, for example, sunlight drying process takes a long time and drying conditions can not be easily controlled, so it is inability to meet the demand for achieving the continuously industrialized standard[7]. Compared to the sunlight drying, hot air drying can improve the drying efficiency, but high temperature caused by hot air drying makes hardening phenomenon of the material surface, and then affects the drying rate, causing a lengthy drying time during the last stage of drying[8]. The quality of crashed cotton stalk by this drying method is frequently not optimal. Compared with sunlight drying and hot air drying, microwave drying has some advantages, including uniform energy and high thermal conductivity to the inner sides of the material, space utilization, energy saving, and fast startup and shutdown conditions, which also reduces the drying time[9]. Microwave drying is widely used in the drying of mint leaves, red pepper, coriander leaves, okra and apple drying[10-14], but the application to dry straw has not been reported.

In addition, the most important aspect of drying technology is the mathematical modeling of the drying process and equipment. Design engineers can use mathematical modeling to choose the most suitable operating conditions and then size the drying equipment and drying chamber accordingly to match the desired operating conditions[15]. Therefore, the aims of the present work were to determine the effects of material load on the efficiency of microwave drying including drying time, drying rate, drying efficiency, and specific energy consumption; to compare the fitting ability of several drying mathematical modeling to express the drying kinetics of crashed cotton stalk with the most suitable drying model and to select the most suitable operations conditions, so as to design drying equipment.

2 Materials and method

2.1 Raw material

Cotton stalks were obtained from an experimental farmland of Northwest A&F University, China, 2014. Before the drying experiments, the cotton stalks were soaked in water 24 h for being fully softened. The softened cotton stalks were twice crashed with cotton stalk fluffer. After one day indoor natural drying, the crashed cotton stalks were cut into samples with the length of 20 cm (close to the width of microwave drying chamber). To make the microwave uniformly passing the dried layer, the samples were horizontally arranged in the microwave chamber during the experiment. Three 20 g crashed cotton stalks samples were dried in an oven at 103±1°C for 24 h to determine initial moisture content[16]. The results showed that the initial moisture content of the crashed cotton stalks was 76% (db).

2.2 Drying equipment and experimental procedure

Drying treatment was performed in a digital microwave dryer (Crown KLT-ZH, China) with maximum power output 1000 W and a frequency of 2450 MHz. Six different amounts of material loads (250 g, 167 g, 125 g, 100 g, 67 g and 50 g) were investigated in drying experiments at 1000 W microwave power. The crashed cotton stalks materials were uniformly spread on the conveyer belt inside the microwave cavity. Three replicates were carried out for each experiment. Depending on the drying conditions, moisture loss of the crashed cotton stalks was recorded at 1 min intervals during drying by using digital balance[16,17]. During the drying process, all weighing processes were completed within 10 s. The microwave power was applied until the moisture content of the sample reduced to about 6%.

2.3 Mathematical modeling of microwave drying curves

To investigate the drying characteristics of crashed cotton stalks, it is important to model the drying behaviour effectively. In this study, six different thin-layer drying models were used (Table 1).

Table 1 Selected thin layer-drying mathematical models

Models	Equations	Reference
Lewis	$MR=\exp(-kt)$	[18]
Page	$MR=\exp(-kt^n)$	[19]
Henderson and Pabis	$MR=a\exp(-kt)$	[20]
Logarithmic	$MR=a\exp(-kt)+b$	[21]
Wang and Singh	$MR=1+bt+at^2$	[11]
Midilli et al.	$MR=a\exp(-kt^n)+bt$	[22]

Note: k, n, a and b are the model constants.

During the drying process, the instantaneous moisture ratio (MR) at any given time can be calculated according to the following equation:

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

where, M_t, M_0 and Me are moisture content at any time of drying (%), initial moisture content (%) and equilibrium moisture content (%), respectively, and t is drying time (min). Me is very small compared to M_t and M_0 for the microwave drying process, thus the MR can be rearranged as[9,13]:

$$MR = \frac{M_t}{M_o} \tag{2}$$

2.4 Computational work

In this study, the nonlinear or linear regression analysis was performed using software IMB SPSS statistics 19. The models were evaluated through coefficient of determination (R^2), root mean square error (RMSE) and reduced chi-square (χ^2). The best model describing the drying characteristics of crashed cotton stalks was the one with the highest R^2, and the lowest χ^2 and RMSE values[18,19]. These parameters are defined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N}(\overline{MR_{\exp,i}} - MR_{pre,i})^2} \tag{3}$$

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

$$RMSE = \left(\frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{N}\right)^{0.5} \tag{5}$$

where, $MR_{\exp,i}$ and $MR_{pred,i}$ are the ith experimental and predicted moisture ratio, respectively; N is the number of observations; z is the number of constants in the drying model.

2.5 Drying rate

The drying rate (DR) was calculated using the following equation:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{6}$$

where, DR represents drying rate (kg water/kg db·min); $M_{t+\Delta t}$ is the moisture content of the sample dried at time $t+\Delta t$ (%) and t is drying time (min).

2.6 Moisture diffusivity

Fick's second equation of diffusion is generally used to describe the drying characteristics of the biological materials, which is used to calculate the effective diffusivity, considering a constant moisture diffusivity, infinite slab geometry and uniform initial moisture distribution[20]:

$$MR = \frac{8}{\pi^2}\sum_{N=0}^{\infty}\frac{1}{(2N+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{7}$$

where, D_{eff} is the effective moisture diffusivity (m^2/s); L is the half thickness of crashed cotton stalk (m) and t is drying time (s).

Considering only the first term of the series is significant, the Equation (7) can be simplified as Equation (8):

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

D_{eff} can be determined by plotting the experimental data of ln(MR) versus time:

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

2.7 Energy efficiency of microwave drying

The effect of material load on the energy efficiency for drying of crashed cotton stalks at 1000 W microwave power was evaluated by two different indicators, which were microwave drying efficiency in % and specific energy consumption in MJ/kg water[16].

The microwave drying efficiency was represented by the ratio of energy generated by the moisture vapor evaporation versus energy provided by the microwave equipment[21].

$$\mu = \frac{m_w\lambda_w}{Pt}\times 100 \tag{10}$$

where, μ is the microwave drying efficiency (%); m_w is the weight of evaporated water (kg); λ_w is the latent heat of vaporization of water (J/kg); P is the average microwave power (W); and t is the time interval (s).

The specific energy consumption of the crashed cotton stalks drying process was expressed in MJ/kg water. So the specific energy consumption could be calculated as follows[20]:

$$E_s = \frac{Pt \times 10^{-6}}{m_w} \tag{11}$$

where, E_s is the specific energy consumption to evaporate a unit mass of water from the product (MJ/ kg water).

3 Results and discussion

3.1 Effect of material load on the drying kinetics of crashed cotton stalks

To investigating the effect of material load on moisture content, drying rate, and drying time, six different material loads, 50 g, 67 g, 100 g, 125 g, 167 g, and 250 g were used for drying of constant microwave power level of 1000 W. The moisture content versus drying time curves for microwave drying of crashed cotton stalks as affected by material load are shown in Figure 1. As the material load was increased, the drying time was obviously increased as well. The microwave drying process which reduced the material moisture contents from 76% to moisture content of 6% took 6-16 min, depending on material load. The higher the material load, the longer the drying time of crashed cotton stalk. Similar findings were also reported by several authors for many products under microwave drying[16]. As the variation in initial moisture contents of the material used in drying experiments were relatively very small, the difference in drying time was considered to be mainly due to the difference in material load.

The drying rates were determined from the amount of water removed per unit time and per unit dry base. As can be seen from Figure 2, the lower material loads, the higher the drying rates. This is because the applied microwave power density for unit mass of dried material decreased with increasing of material load. It is also clear from the Figure 2 that all the drying rates-t curves have two stages during the drying process. The drying rate firstly rapidly increases and then slowly decreases as drying progresses. In general, it is observed that drying rate decreased with time or the reduction of moisture content. This is because the moisture content of the material was very high during the initial stage 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 process proceeded, 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[11,16]. The drying process mainly took place in the falling rate period. These results are consistent with the findings reported about the drying of different fruits and vegetables[9,11,22].

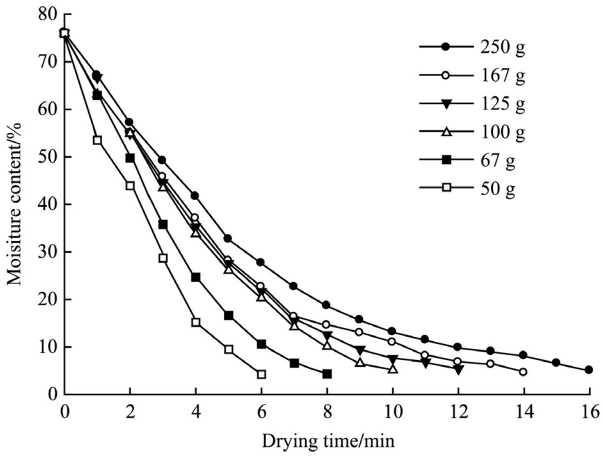

Figure 1 Relationship between the moisture content (%) and drying time at different material load

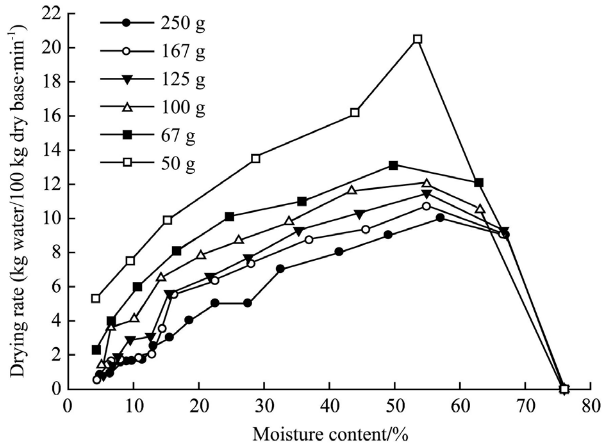

Figure 2 Relationship between the drying rate and moisture content (%) at different material load

3.2 Modeling of drying curves

As shown in Table 2, six thin-layer drying models were tested for their suitability to explain the moisture of samples during drying. According to the evaluation criteria of mathematical model for the match[18,19], among these models, Midilli et al. model was observed as the most appropriate for all experimental data with values for the coefficient of determination greater than 0.9942 and χ^2 values and RMSE values lower than 0.0051 and 0.0243, respectively. Thus, Midilli et al. model could better represent the microwave drying behavior of crashed cotton stalks compared to other models listed.

Table 2 Values of the drying constants and coefficients of different models determined through regression method for different material load

Model	Material load/g	Model Constants	R^2	χ^2	RMSE
Lewis	250	k=0.1659	0.9970	0.0080	0.0195
	167	k=0.1932	0.9952	0.0133	0.0263
	125	k=0.2040	0.9943	0.0229	0.0331
	100	k=0.2169	0.9900	0.0423	0.0423
	67	k=0.2785	0.9867	0.0492	0.0497
	50	k=0.3588	0.9819	0.0403	0.0470
Henderson and Pabis	250	a=1.0325; k=0.1715	0.9969	0.0058	0.0044
	167	a=1.0432; k=0.2017	0.9948	0.0085	0.0216
	125	a=1.0538; k=0.2152	0.9929	0.0132	0.9929
	100	a=1.0458; k=0.2273	0.9876	0.0327	0.0358
	67	a=1.0582; k=0.2946	0.9834	0.0371	0.0438
	50	a=1.0213; k=0.3665	0.9807	0.0374	0.0461
Logarithmic	250	a=1.0391; k=0.1673; b=−0.0098	0.9970	0.0068	0.0158
	167	a=1.0601; k=0.1899; b=−0.0243	0.9952	0.0104	0.0206
	125	a=1.1166; k=0.1804; b=−0.1806	0.9956	0.0125	0.0203
	100	a=1.2453; k=0.1499; b=−0.2339	0.9976	0.0068	0.0150
	67	a=1.2730; k=0.1911; b=−0.2475	0.9953	0.0134	0.0222
	50	a=1.2879; k=0.2224; b=−0.2967	0.9933	0.0072	0.0261
Midilli et al.	250	a=0.9993; k=0.1260; b=0.0029; n=1.1865	0.9993	0.0032	0.0077
	167	a=1.0017; k=0.1392; b=0.0032; n=1.2332	0.9987	0.0051	0.0106
	125	a=0.9991; k=0.1334; b=0.0027; n=1.2870	0.9998	0.0006	0.0043
	100	a=0.9981; k=−0.0733; b=−0.2317; n=1.0747	0.9991	0.0009	0.0090
	67	a=0.9960; k=0.1692; b=− 0.0010; n=1.3510	0.9997	0.0004	0.0059
	50	a=0.9845; k= −0.0630; b=−0.3063; n=1.3059	0.9942	0.0042	0.0243
Wang and Singh	250	a=0.0047; b=−0.1313	0.9957	0.0238	0.0191
	167	a=0.0062; b=−0.1510	0.9950	0.0233	0.0211
	125	a=0.0070; b= −0.1603	0.9988	0.0028	0.0118
	100	a=0.0072; b=−0.1659	0.9990	0.0011	0.0096
	67	a=0.0114; b=−0.2104	0.9981	0.0033	0.0159
	50	a=0.1856; b=−0.2690	0.9936	0.0046	0.0261
Page	250	k=0.1386; n=1.0937	0.9980	0.0090	0.0131
	167	k=0.1509; n=1.1399	0.9974	0.0113	0.0156
	125	k=0.1413; n=1.2175	0.9992	0.0048	0.0086
	100	k=0.1423; n=1.2628	0.9980	0.0032	0.0140
	67	k=.1707; n=1.3590	0.9996	0.0003	0.0065
	50	k=0.2761; n=1.2314	0.9885	0.0128	0.0346

Under the drying conditions of different material loads (250 g, 167 g, 125 g, 100 g, 67 g and 50 g), a comparison of the experimental and predicted moisture ratio values using the Midilli et al. model was illustrated in Figure 3. As can be observed in the figure, consistency of fitting the drying data into this model was very good under all of the experimental drying conditions. Thus, the Midilli et.al model may be assumed to accurately simulate the variation regularity of the rate for moisture loss in the microwave drying process[18].

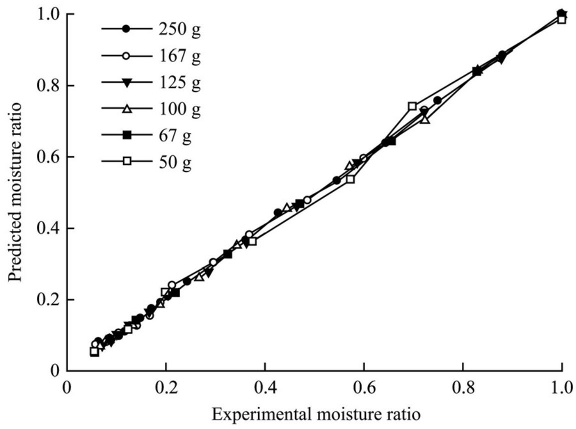

Figure 3 Experimental moisture ratio versus predicted moisture ratio of crashed cotton stalks with Midilli et al. model

In order to interpret the effect of material load on the Midilli et al. model coefficients, the constants a, b, n and k were regressed against the material load using multiple regression analysis. Based on the regression analysis, the accepted model and their constants are as follows:

$$MR = a\exp(-kt^n) + bt$$

$$a = -4\times10^{-10}m^4 + 2\times10^{-7}m^3 - 4\times10^{-5}m^2 + 0.003m + 0.876 \quad (R^2 = 0.984)$$

$$k = 6\times10^{-10}m^5 - 4\times10^{-7}m^4 + 10^{-4}m^3 - 0.011m^2 + 0.606m - 11.77 \quad (R^2 = 1)$$

$$b = 8\times10^{-10}m^5 - 5\times10^{-7}m^4 - 0.015m^2 + 0.830m - 17.04 \quad (R^2 = 1)$$

$$n = 6\times10^{-10}m^5 - 4\times10^{-7}m^4 - 0.011m^2 + 0.6m - 10.22 \quad (R^2 = 1)$$

3.2 Calculation of effective moisture diffusivity for different material loads dried

The determined values of effective moisture diffusivity (D_{eff}) for different material load dried are given in Table 3. It can be seen that D_{eff} are within 2.8668×10^{-8}-7.9817×10^{-8} m^2/s from 250 g to 50 g, respectively. The D_{eff} values of the samples were within the general ranges of 10^{-6}-10^{-11} m^2/s for biological and food materials[11,12,20].

There is no research result was found regarding the effect of sample mass on D_{eff} for crashed cotton stalks in the literature. Therefore, in this study, D_{eff} was investigated by using the method of slopes, the logarithm of moisture ratio values, lnMR, was plotted against drying time (t) according to the experimental data obtained for different material loads dried in the range of 50-250 g at 1000 W microwave output power. The values of D_{eff}, the corresponding values of coefficients of determination are presented in Table 3 for each sample amount. It can be seen that the values of D_{eff} increased with decreasing sample amount. The linearity of the relationship between lnMR and drying time (t) is also illustrated in Figure 4 for each sample amount. The sample amount and effective moisture diffusivity values were inversely proportional to each other as seen from Table 3 and Figure 4. This might be explained by the increased heating energy, because of high energy transferred to the material and rapid heating, the vapor pressure inside the product increased, and this caused faster diffusion of moisture to the surface at lower sample amounts[20].

Table 3 Regression equation and correlation analysis at various sample amounts

Material load/g	Regression equation	R^2	$D_{eff}\times10^{-8}$/m^2·s^{-1}
250	$\ln MR=-2.8294\times10^{-3}t+0.0895$	$R^2=0.9955$	2.8668
167	$\ln MR=-3.4080\times10^{-3}t+0.0430$	$R^2=0.9951$	3.4530
125	$\ln MR=-3.8835\times10^{-3}t+0.1032$	$R^2=0.9955$	3.9348
100	$\ln MR=-4.6103\times10^{-3}t+0.1897$	$R^2=0.9826$	4.6742
67	$\ln MR=-6.1557\times10^{-3}t+0.2211$	$R^2=0.9837$	6.2370
50	$\ln MR=-7.8776\times10^{-3}t+0.2016$	$R^2=0.9661$	7.9817

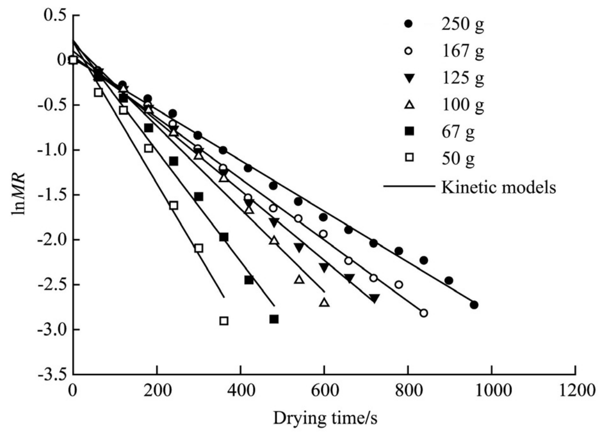

Figure 4 Linear relationship between lnMR and drying time at various sample amounts of crashed cotton stalks

3.3 Effect of material load on the energy efficiency of microwave drying

Effect of material load on the energy efficiency of microwave drying was evaluated by two different efficiency indices as microwave drying efficiency in % and specific energy consumption in MJ/kg H_2O. The changes of the microwave drying efficiency with moisture content for various material loads were illustrated in Figure 5. Although the microwave drying efficiency for crashed cotton stalks differed between material loads, the microwave drying efficiency showed a rapidly increasing tendency to a moisture content of about 60% (db.). Apparently, during the initial few minutes, the microwave energy applied was used in raising the material temperature and very little moisture was evaporated (Figures 2 and 5). The drying efficiency was very high during the initial phase of the drying, which resulted in a higher absorption of microwave power. As the drying proceed, the loss of moisture in the product caused a decrease in the absorption of microwave power[16,21]. For this reason, it was observed that with the material load increasing, the energy losses decreased, in other words drying efficiency values increased. Similar trends were also observed by Soysal et al.[16] for microwave drying of parsley.

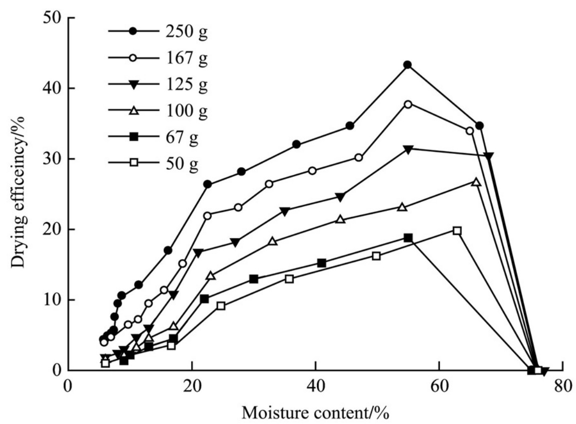

Figure 5 Variation in drying efficiency with moisture content at various sample amounts of crashed cotton stalks

But, in this study, it should be noted that the range of material load is limited to 50-250 g. In the range, a considerable increase in drying efficiency with increasing material load signifies that the microwave was efficiently absorbed by water[21,23]. As the size of load relative to cavity determines the amount of power reflection back to the magnetron, the larger the load size, the lower the power reduction by reflection and cavity loss and, hence, the higher the efficiency of power absorption[16,24].

Under the different material loads conditions, specific energy consumption of crashed cotton stalks drying was shown in Figure 6. It was clear that specific energy consumption decreased continuously with the increasing of material load (50-250 g), and the scope of the specific energy consumption value ranged from 10.99 MJ/kg water to 22.13 MJ/kg water. The higher the material loads, the lower the specific energy consumption (Figure 6). As the intensity of heat generation is proportional to the content of moisture in a dielectric dried material, the bigger the amount of water trapped inside the material provided the higher drying efficiency and the lower specific energy consumption values[16,25].

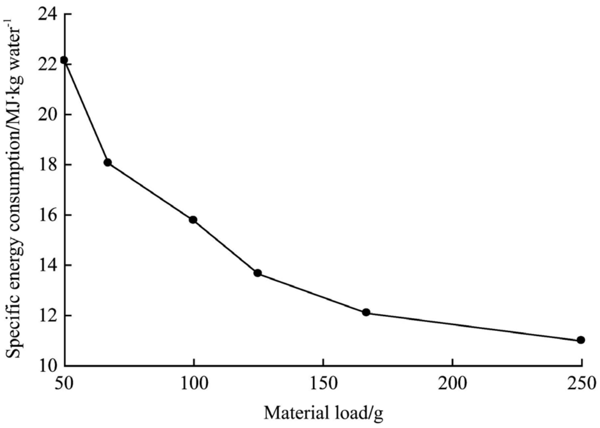

Figure 6 Specific energy consumption at various sample amounts of crashed cotton stalks

4 Conclusions

Microwave drying characteristics of crashed cotton stalks at various sample amounts was investigated in this study. Based on the results of this study, the following conclusions were drawn:

1) Drying time decreased considerably with the decrease of crashed cotton stalk's amount by using microwave drying technique. This technique can be successfully used to dry crashed cotton stalks compared to sun drying and hot air drying.

2) Drying took place mainly in the falling rate period followed by an increasing rate period after a short heating period. Higher drying rates were obtained with lower material loads.

3) Among the six models tested, the Midilli et al. model was found suitable for the description of microwave drying kinetics of crashed cotton stalks with higher coefficient of determinations and lower standard error of estimates.

4) The effective moisture diffusivity increased with the decrease of material load. In the material load range of 50-250 g, the average effective diffusivity varied from 7.9817×10^{-8} m^2/s to 2.8668×10^{-8} m^2/s.

5) When the material load being dried was higher, more of the microwave energy was used for evaporating moisture while the lower material load tended to decrease the drying efficiency and increase the specific energy consumption. The specific energy consumption was in the scope from 22.13 MJ/kg to 10.99 MJ/kg water in the material load range of 50-250 g.

The model and parameters found in this study can provide operational guides for microwave drying of crashed cotton and equipment designs. There is a contradiction between drying time and energy consumption, in order to obtain the best drying benefit of crashed cotton stalks, the further research will be performed to study the relationship between energy consumption and the microwave power density.

Acknowledgement

This work was supported by the Special Fund for Agro-scientific Research in the Public Interest of Agricultural biomass characteristics and Sharing platform technology research (project number: 201003063).

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