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Drying Characteristics of Powdered Wheat Straw and Its Mathematical Modeling

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ABSTRACT

The objective of this research was to study the drying characteristics of powdered agricultural residues. Drying experiments of wheat straw (*Triticum aestivum*) were conducted at four temperatures of 50, 60, 70, and 80°C by a thermogravimetric analyzer. Drying temperature had a significant effect on the moisture change and drying time. There was no constant drying rate period, but a short rising rate period was evident for all drying process due to increasing temperature of the sample at the beginning of drying. Six mathematical models were selected to describe the drying characteristics of wheat straw. The goodness of fit was evaluated by the coefficient of determination (R^2), the reduced chi-square (χ^2), and the root mean square error (RMSE). Midilli *et al.* model was found to be the best for modeling the experimental data. The values of effective moisture diffusivity of wheat straw dried at 50, 60, 70, and 80°C were calculated to be 1.13×10^{-8}, 1.48×10^{-8}, 1.66×10^{-8}, and 2.29×10^{-8} $m^2\ s^{-1}$, respectively.

Keywords: Biomass, Effective moisture diffusivity, Isothermal condition, Midilli model, Thermogravimetric analysis.

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INTRODUCTION

Biomass is an ideal renewable source of energy and has received much attention. China possesses abundant biomass resources, including annual output of wheat straw as many as 15 million tons (Zhou *et al.*, 2011). Thus, it is essential to utilize agricultural straw efficiently, as it is not only an important biomass-based energy source for gas and liquid fuel and biochar production, but also a good way to solve the climate warming problems (Vispute *et al.*, 2010). The major techniques for biomass utilization are thermochemical conversions (e.g. pyrolysis), which require dried and powdered biomass (Lu *et al.*, 2011). However, the moisture content of agricultural residues is often high, generally in the range of 7~63% depending on the season (Chen *et al.*, 2009). High moisture content tends to reduce the net energy density, hinder the combustion of reaction products, and affects the performance and reliability of biomass. Therefore, dry pretreatment of powdered biomass is essential to minimize the effect of moisture on biomass utilization.

Recently, drying studies have been carried out on various biological materials such as soybean (Rafiee *et al.*, 2009), seeds (*cuminum cyminum*) (Zomorodian and Moradi, 2010), oyster mushroom (Tulek, 2011), quercus fruit (Tahmasebi *et al.*, 2011), barberry fruit (Gorjian *et al.*, 2011), pomegranate (Minaei *et al.*, 2012), carrot (Srikiatden and Roberts, 2006), potato (Doymaz, 2010), bean (Li and Kobayashi, 2005), blueberries (Shi *et al.*, 2008) and sawdust (Chen *et al.*, 2012). However, few studies have been conducted for agricultural residues such as wheat straw. In addition, kinetics analysis contributes to further understanding the drying mechanisms and prediction of the drying process (Vega-

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Gálvez *et al.*, 2010). Various mathematical models have been proposed to describe the drying process of biomass (Di Scala and Crapiste, 2008). However, the mathematical models are mainly applied to the massive, cylindrical, and spherical materials. Little attention has been paid to powdered biomass.

Thermogravimetric analysis (TGA) is a useful tool for kinetics analysis of biomass. It has precise temperature control capability which can achieve isothermal condition rapidly. For biomass drying, it also has some other advantages such as ease of operation, minimal requirement of sample, and online recording of weight loss.

The objectives of this study were to determine experimentally the drying characteristics of powdered wheat straw under isothermal condition by TGA, and to select the best mathematical model for the drying curves.

MATERIALS AND METHODS

Materials

Wheat straw (*Triticum aestivum*) used in this study was selected from local suburbs. Wheat straw was ground in a disintegrator and the particles with the size of 0.125–0.3 mm were chosen for experiments. The bulk density of wheat straw was 35 kg m^{-3}. The samples were conserved in a sealed vitreous container for 96 hours to allow the moisture to distribute evenly. The moisture content was determined by drying in an oven at 105ºC for six hours until no mass loss occurred between the two weighing intervals. As an average of the results, the initial moisture content of wheat straw was found to be 0.082 g water g^{-1} dry matter.

Experimental Procedure

A thermogravimetrical analyzer (TGA Q5000IR, TA Instruments, USA) was used to perform the drying experiments. The main technical parameters are expressed as follows: weighing accuracy, ±0.1%; weighing sensitivity, < 0.1 μg; weighing range, 0 to 100 mg; temperature range, ambient to 1,200°C; heating rate, 0.1 to 500 °C min^{-1}; and isothermal temperature accuracy, ±1°C. A computer connected to the TGA automatically recorded the weight change with time, and then processed the data.

In this study, the drying experiments were performed at four temperatures (50, 60, 70 and 80°C). About 9 mg of the sample was used, and the air flow rate was maintained at 100 mL min^{-1} for each experiment. The sample was first spread in a sample pan (platinum) and the furnace temperature was set to the required drying temperature. Afterwards, TGA automatically placed the sample pan in the furnace and the experiment started. The sample was heated to the drying temperature rapidly. The time of heating up period was generally 1 minute. Each experiment was performed in triplicate to decrease experimental error. These selected conditions indicated a thin-layer drying, and were in agreement with some previous drying studies by TGA (Chen *et al.*, 2012; Hu *et al.*, 2012; Li and Kobayashi, 2005).

Equilibrium Moisture Content

The equilibrium moisture content of wheat straw at the different temperatures in this study was determined by dynamic method according to the previous studies (Chen *et al.*, 2012; Lee *et al.*, 2012; Rafiee *et al.*, 2009). The sample was exposed to different air temperatures (50, 60, 70 and 80°C) and constant relative humidity (20%) in a thin-layer dryer for 6-10 days until the mass loss ceased. Then, the sample was taken out and the moisture content was determined by the oven drying method. The determined values were the equilibrium moisture contents, which were 3.0, 2.4, 2.0, and 1.7% (db) for drying at 50, 60, 70, and 80°C, respectively.

Mathematical Modeling of Drying Curves

The moisture ratio (MR) of biomass was calculated by the following equation:

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

Where, M is the moisture content at any time (g water g^{-1} dry matter), M_0 is the initial moisture content (g water g^{-1} dry matter), and M_e is the equilibrium moisture content (g water g^{-1} dry matter).

The drying curves obtained by TGA were fitted with six commonly used drying models proposed by different authors given in Table 1 (Akpinar *et al.*, 2003; Henderson and Pabis, 1961; Lewis, 1921; Midilli *et al.*, 2002; Page, 1949; Wang and Singh, 1978).

The regression analysis was performed using the Origin 8.0 software. The statistical parameters used to evaluate the fitting goodness of predicted values to experimental values were the coefficient of determination (R^2), the reduced chi-square (χ^2), and the root mean square error (RMSE).

χ^2 and $RMSE$ can be calculated as follows.

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

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\text{pre},i} - MR_{\text{exp},i})^2\right]^{1/2} \qquad (3)$$

Where, $MR_{\text{exp},i}$ and $MR_{\text{pre},i}$ are experimental and predicted moisture ratios, respectively; N is number of observations, and n is number of drying constants. The best model for describing the drying characteristics of wheat straw was selected with the highest value of R^2 and the lowest value of χ^2 and $RMSE$.

Determination of Effective Moisture Diffusivity

The Fick's second law of diffusion, as shown in Equation (4), has been widely used to describe the drying process and determine the effective moisture diffusivity.

$$\frac{\partial MR}{\partial t} = \nabla[D_{\text{eff}}(\nabla MR)] \qquad (4)$$

The solution of Equation (4) is shown in Equation (5), assuming constant temperature, moisture transport being only by diffusion, uniform initial moisture distribution, and negligible shrinkage (Ashraf *et al.*, 2012).

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{\text{eff}} t}{4L^2}\right) \qquad (5)$$

Where, t is the drying time (min), L is the half thickness of the sample (m), and n is a positive integer. In this study, D_{eff} was determined by non-linear regression. The maximum value of n was set to 1000. The mathematical software, Origin 8.0, was used for this purpose.

RESULTS AND DISCUSSION

Drying Characteristics of Wheat Straw

The moisture content (Y axis) of the sample as a function of drying time (X axis) is shown in Figure(1-a). It can be seen that moisture change at different drying temperatures showed a similar trend, which was rapidly reducing and then slowly decreasing with drying time. Temperature had a significant effect on the moisture content and drying time. The higher the drying temperature, the more moisture was removed. The final moisture content was 3.2% (db) for drying at 50°C, whereas it was

Table 1. Mathematical models applied to drying curve of wheat straw.

Model	Equation	Reference
Page	$MR = \exp(-kt^n)$	(Page, 1949)
Lewis	$MR = \exp(-kt)$	(Lewis, 1921)
Logarithmic	$MR = a+b\exp(-kt)$	(Akpinar *et al.*, 2003)
Henderson and Pabis	$MR = a\exp(-kt)$	(Henderson and Pabis, 1961)
Wang and Sing	$MR = 1+at+bt^2$	(Wang and Singh, 1978)
Midilli *et al.*	$MR = a\exp(-kt^n)+bt$	(Midilli *et al.*, 2002)

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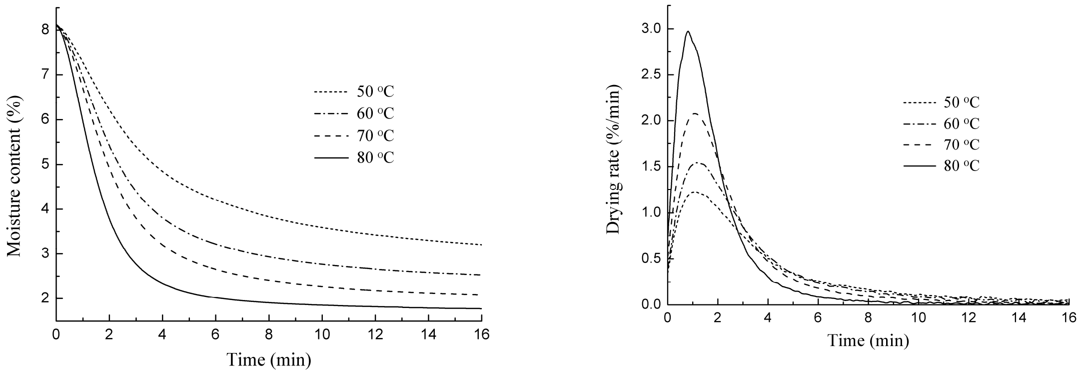

(a)

(b)

Figure 1. Drying curves of wheat straw (a) Drying rate curves of wheat straw (b) at different temperatures.

1.8% (db) for drying at 80°C. For pyrolysis utilization of biomass, it is appropriate to reduce the moisture content below 3%. However, the final moisture content was higher than 3% (db) when the sample was drying at 50°C as the temperature was relatively low. The time required to achieve specific moisture content decreased notably with increasing drying temperature. For example, it took 2.8, 4.6, and 7.3 minutes for drying at 80, 70, and 60°C, respectively, to achieve the moisture content of 3% (db). Similar results were obtained by different researchers (Minaei *et al.*, 2012; Shi *et al.*, 2008; Tahmasebi *et al.*, 2011).

The changes in drying rate with drying time at different temperatures were also measured by TGA, and are shown in Figure(1-b). As indicated in this figure, there was no constant drying rate period but a short rising rate period was evident in the beginning of drying. This phenomenon was reported by different researcher. Hu *et al.* studied the drying characteristics of cotton stalk by TGA. The results showed that cotton stalk with different moisture contents shared a similar drying process that can be divided into three periods: preheating (rising rate), constant, and falling (Hu *et al.*, 2012). Chen *et al.* also founded that there was a rising rate period occurring in the drying process of sawdust, and that this period would be more significant when the moisture content of the material was higher (Chen *et al.*, 2012). Shi *et al.* pointed out that a short rising rate period appearing was due to the sample temperature increased in the initial drying process (Shi *et al.*, 2008). Chen *et al.* studied the nonisothermal drying characteristics of cotton stalk (Chen *et al.*, 2011). The results indicated that the rising rate period corresponded to evaporation of free water, which had a weak bonding force with the material. TGA can not only real-time measure the weight loss, but also record the temperature change of biomass. Figure 2 shows the temperature profiles of the sample. It can be seen that isothermal drying condition was established after a heating up period within 50 seconds. Particularly, the rising drying rate took place in this heating up period. Therefore, the occurring of rising rate period could be attributed to increasing temperature of the sample. These results were generally in agreement with some other reports (Li and Kobayashi, 2005; Shi *et al.*, 2008; Srikiatden and Roberts, 2006).

Evaluation of the Models

The moisture ratio obtained by TGA was fitted to the selected drying models in order

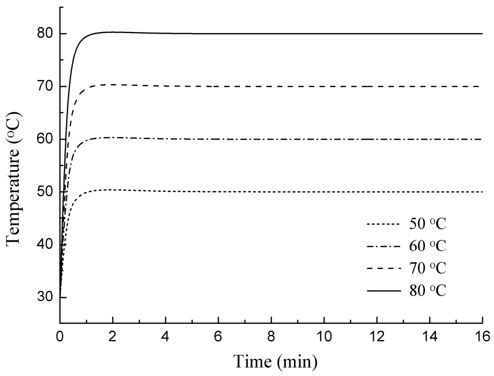

Figure 2. Temperature profiles of wheat straw under isothermal drying condition.

to describe the drying characteristics of wheat straw under isothermal condition. The fitting goodness of the six models, namely, Page model, Lewis model, Logarithmic model, Henderson and Pabis model, Wang and Sing model, and Midilli *et al.* model, was evaluated based on χ^2, R^2 and *RMSE*. The higher the R^2 value and the lower the χ^2 and *RMSE* values, the better is the goodness of fit. The fitting results are presented in 2.

Acceptable R^2 values (> 0.98) were obtained for all models, except Wang and Sing model. As seen in Table 2, Midilli *et al.* model showed the best agreement for the experimental data. The R^2, χ^2, and *RMSE* values of Midilli *et al.* model were 0.99631–0.99815, 0.00013–0.00023, and 0.00213-0.00952, respectively. The drying parameters of Midilli *et al.* model are also listed in Table 2. It can be seen that the drying rate constant increased with increasing drying temperature. For example, when air temperature was 50 and 80°C, *k* was 0.28260 and 0.50333, respectively.

Midilli *et al.* model was selected to describe the drying characteristics of wheat straw. The comparison between predicted and experimental values of moisture ratio is shown in Figure 4. Good correlation can be observed from the linear nature of the curve. The fitting results of wheat straw drying at temperatures of 50, 60, 70 and 80°C are shown in Figure 5. It is clear that Midilli *et al.* model represented the experimental data perfectly well.

Determination of Effective Moisture Diffusivity

The drying rate started to decrease when the required drying temperature was achieved. The falling rate period was the main drying process, and the moisture movement in this period was governed by internal diffusion. However, the short rising rate period was different from the falling rate period. Figure 2 clearly indicates that it was not a diffusion process. This period was excluded from the determination of the effective moisture diffusivity for obtaining accurate results. Thus, Equation (1) was replaced by $MR = (M-M_e)/(M_{to}-M_e)$, where t_o is the beginning time of the falling rate period (Chen *et al.*, 2012).

The calculated values of effective moisture diffusivity were 1.13×10^{-8}, 1.48×10^{-8}, 1.66×10^{-8}, and 2.29×10^{-8} m^2 s^{-1} at 50, 60, 70, and 80°C, respectively. The effective moisture diffusivity increased with increasing drying temperature due to more energy being provided. The values obtained in our study were generally in the range of 10^{-10} to 10^{-8} m^2 s^{-1} for forestry and agricultural residues (Erbay and Icier, 2010).

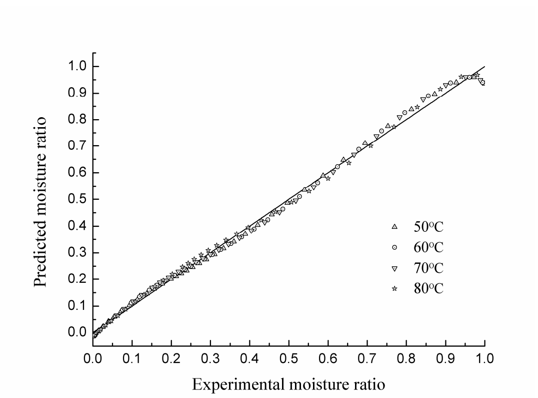

Figure 4. Comparison of experimental and predicted moisture ratio by Midilli *et al.* model for wheat straw.

Table 2. Statistical results of the different drying models.

Model	Temperature (°C)	Parameters (k min^{-1})	R^2	χ^2	*RMSE*
Page	50	*k*= 0.23524 *n*= 1.06244	0.99651	0.00024	0.01315
	60	*k*= 0.29731 *n*= 1.10394	0.99353	0.00042	0.01587
	70	*k*= 0.32407 *n*= 1.15091	0.99319	0.00042	0.01633
	80	*k*= 0.44373 *n*= 1.26993	0.99468	0.00027	0.01036
Lewis	50	*k*= 0.25893	0.99533	0.00023	0.02178
	60	*k*= 0.33820	0.99108	0.00056	0.01906
	70	*k*= 0.38274	0.98886	0.00069	0.02275
	80	*k*= 0.54189	0.98474	0.00078	0.02608
Logarithmic	50	*k*= 0.27912 *a*= 0.00569 *b*= 1.05580	0.99804	0.00014	0.01083
	60	*k*= 0.38276 *a*= 0.01146 *b*= 1.08500	0.99662	0.00022	0.01121
	70	*k*= 0.43637 *a*= 0.00963 *b*= 1.10189	0.99588	0.00026	0.01355
	80	*k*= 0.62261 *a*= 0.00539 *b*= 1.13268	0.99442	0.00029	0.01073
Henderson and Pabis	50	*k*= 0.27370 *a*= 1.05670	0.99794	0.00014	0.01256
	60	*k*= 0.36711 *a*= 1.08522	0.99589	0.00027	0.01087
	70	*k*= 0.42149 *a*= 1.10202	0.99523	0.00030	0.00979
	80	*k*= 0.61131 *a*= 1.13308	0.99407	0.00031	0.01322
Wang and Sing	50	*a*= 0.00569 *b*= -0.17046	0.94749	0.00368	0.18325
	60	*a*= 0.00871 *b*= -0.19228	0.87512	0.00808	0.09756
	70	*a*= 0.00933 *b*= -0.20106	0.82485	0.00108	0.11552
	80	*a*= 0.01071 *b*= -0.22018	0.57328	0.02180	0.35621
Midilli *et al.*	50	*k*= 0.28260 *n*= 0.98623 *a*= 1.06538 *b*= 0.00013	0.99815	0.00013	0.00213
	60	*k*= 0.35213 *n*= 1.04165 *a*= 1.07411 *b*= 0.00097	0.99670	0.00021	0.00838
	70	*k*= 0.38086 *n*= 1.08448 *a*= 1.07092 *n*= 0.00101	0.99631	0.00023	0.00952
	80	*k*= 0.50333 *n*= 1.18965 *a*= 1.05706 *b*= 0.00076	0.99673	0.00017	0.00816

CONCLUSIONS

The drying characteristics of powdered wheat straw were investigated by TGA. Drying temperature had a significant effect on the moisture change and drying time. With higher drying temperature, more moisture was removed and less time was required achieving specific moisture content. The falling rate period dominated the drying process. A short rising rate period occurred due to increasing temperature of the sample at the beginning of drying. Six different mathematical models were selected to describe the drying characteristics of wheat straw. Midilli *et al.* model gave the best fit for all drying tests. The short rising rate period was excluded from the determination of the effective moisture diffusivity for obtaining accurate results. The values of effective moisture diffusivity were determined as 1.13×10^{-8}, 1.48×10^{-8}, 1.66×10^{-8}, and 2.29×10^{-8} m^2 s^{-1} at 50, 60, 70, and 80°C, respectively.

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ویژگی های فرایند خشک کردن پودر کاه گندم و شبیه سازی ریاضی آن

د. چن، م. لی، و ز. ژو

چکیده

هدف این تحقیق بررسی ویژگی های خشک کردن پودر پسمانده های کشاورزی بود. آزمایش های خشک کردن کاه گندم (*Triticum aestivum*) در چهار درجه حرارت ۶۰، ۵۰، ۷۰، و ۸۰ درجه سانتی گراد و با استفاده از دستگاه تجزیه کننده گرمایی-گرانشی (ترموگراویمتر) انجام شد. درجه حرارت خشک کردن اثر معنی داری روی تغییرات رطوبت و طول زمان خشک کردن داشت. در این آزمایش هیچ دوره زمانی با نرخ خشک شدن ثابت مشاهده نشد، اما، در همه آزمایش ها دردوره کوتاهی در ابتدای کار، نرخ مزبور

افزایشی بود که علت آن زیاد شدن درجه حرارت نمونه مورد مطالعه بود. برای تشریح و شبیه سازی ویژگی های خشک شدن پودر کاه گندم، شش مدل ریاضی انتخاب شدند و برای ارزیابی برازندگی (نکوئی برازش) آنها، از ضریب تبیین (R^2) وکای اسکوئر کاهش یافته (χ^2) و ریشه میانگین مربعات خطا (RMSE) استفاده شد. در میان آن مدل ها، مدل Midilli و همکاران برای شبیه سازی داده های آزمایش بهترین مدل بود. مقادیر پخشیدگی موثر رطوبت کاه گندم که در درجه حرارت های ۵۰،۶۰، ۷۰، و ۸۰ درجه سانتی گراد خشک شد به ترتیب برابر 1.13×10^{-8} m^2/s، 1.48×10^{-8}، 1.66×10^{-8}، و 2.29×10^{-8} m^2/s محاسبه شد.