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Effect of operating conditions on drying of Chinese lignite in a vibration fluidized bed

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ABSTRACT

The drying performance of Chinese lignite particles in a laboratory scale vibration fluidized bed dryer was investigated under various operating conditions: inlet air temperature (120–200 °C), superficial air velocity (1.5 U_{mf} (the minimum fluidization velocity)–2.2 U_{mf},), frequency (10–50 Hz), amplitude (1–5 mm), particle size (0.5–6 mm) and bed height (20–60 mm). The drying results showed that higher temperature, larger air velocity, higher frequency and higher amplitude (not too high), smaller particle size and lower bed height were favorable for drying. The Midilli–Kucuk model provided the best fit of these drying results and further implied that the moisture transfer of lignite was mainly controlled by internal diffusion. In comparison with the case of an ordinary fluidized bed, the gas-vibro fluidized bed dryer exhibited improvement of drying characteristics. Moreover, the drying kinetics was largely dependent on the frequency and amplitude of vibration.

1. Introduction

Low rank coals (LRCs), which are mainly lignites and sub-bituminous coals, account for more than half of the world coal reserves [1,2]. In China, LRCs especially lignites are playing a significant role in supplying primary energy because of their abundance, easy access, and low mining cost [3]. However, their high moisture content (20–55 wt.%) results in lower calorific value, higher fuel consumption, lower efficiency, risk of spontaneous combustion, and increased transportation cost [4,5]. Thus, there is considerable interest in the drying of coal prior to use, transport, or storage.

Allardice et al. [6] and Osman et al. [7] recently reviewed several types of technologies for lignite drying such as rotary tube drying [8], fluidized bed drying [9–12], mechanical thermal dewatering (MTE) [13–15], hydrothermal dewatering (HTD) [16,17], solvent dewatering [18], etc. Each drying technologies had its merits and disadvantages [7]. For instance, the most commonly used driers were the rotary drum type; however, it suffered higher energy consumption and construction costs. Although the newly developed non-evaporative dewatering technologies (HTD and MTE) exhibited cost-effectiveness and energy-efficiency, they required quite high temperatures and high pressure, thus making the processes expensive [7]. Apart from that, they might also have to sustain wastewater treatment and disposal. The fluidized bed dryer had such merits including high drying rate, high processing capacity, and low maintenance cost and these advantages offered a desirable choice for lignite drying [10]. On the other hand, the fluidized bed had some disadvantages, such as unsuitability for the irregularly shaped particles or particles with a wide size distribution [5], and production of substantial amounts of coal fines [2].

Fortunately, there were several effective ways to overcome these disadvantages of the common fluidized bed. Application of mechanical vibration to the fluidized bed (gas-vibro fluidization) was one of the most successful modifications that have found industrial applications [19], although the reliability of structure and the development of low-energy-consumption vibration equipment were the main concerns [4]. The gas-vibro fluidized bed dryer could be used as a strategy to allow easy fluidization for irregular and wide distributed materials (such as lignite particles), to refrain from troubles like channeling, defluidization or slug flow as well as to improve the drying performance of particle in a common fluidized bed [20,21]. Furthermore, mechanical vibration permitted to process moist material with 30–50% less air than in a conventional fluidized bed, therefore, which made it possible to reduce energy consumption and elutriation of moist materials [22].

Due to their unique properties, various aspects associated to vibration fluidization including hydrodynamic characteristics [23], particle separation [24,25] and mixing [26,27], heat transfer [28], two-fluid model [29] and discrete particle model simulation [30], and many industrial applications such as drying [31] have been conducted. A great variety of ceramics [32], mining [33], and feeding products [34,35] were extensively dried in a gas-vibro fluidized bed. However, little information was available and probably could not be applied to lignite drying considering characteristic differences among moist materials. In addition, many studies have also demonstrated that the drying characteristics were dependent on the effect of operation conditions [36]. Less research has been done concerning the effect of operating

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conditions in a gas-vibro fluidized bed on the drying characteristics of lignite, which would be essential in designing of a lignite drying system.

The aim of this work was to study the influence of the operational parameters on the drying characteristics in a laboratory scale gas-vibro fluidized bed dryer. Thus, the effects of inlet air temperature, superficial air velocity, the vibration strength, particle size and bed height were systematically evaluated. In addition, the thin layer drying equation was used to describe the drying kinetics.

2. Experiment

2.1. Lignite properties

A typical Chinese lignite sample (Dayan coal in east of Internal Mongolia) is used in this study. The proximate analysis is listed in Table 1. This sample was crushed and sieved to three size fractions (0.5–1, 1–3 and 1–6 mm). All experiments were carried out with an equal mass of lignite as received basis. To determine the initial moisture content, 2 g sample was dried in an oven at 105 °C for 2 h using a digital balance (Sartorius BT 224 S, with a precision of 0.1 mg).

2.2. Experimental apparatus

Fig. 1 displays a schematic diagram of the experimental apparatus used in this work. An air flow was supplied via a compressor and passed through an electric heater using a temperature controller attached to the heater. The airflow rate was controlled with a valve and measured using a rotameter. Then the resulting hot air entered the stainless steel plenum chamber and passed through the distributor plate. The perforated plate distributor consisted of 2-mm-thick stainless steel with 10% open area. It was supported on a high-temperature filter cloth to prevent particles from falling down into the plenum chamber. The vertical fluidizing bed was made of stainless steel, with size ($W \times H \times L$) of $0.2 \times 0.4 \times 0.2$ m^3. This column was also insulated with glass wool to prevent heat losses. A manometer was kept at different locations of the bed for the measurement of pressure drop across the bed. At the top of the bed, a bag filter was provided for separating fines and gas. An electromagnetic vibration system (DC-600-6), which was manufactured by China STI Co., Ltd., served as the vertical shaker. Its operational conditions were easily adjusted by a digital controller (RC-2000) to generate vibration motions with amplitude ranging from 0 mm to 10 mm and frequency ranging from 1 Hz to 400 Hz. By taking both frequency and amplitude into account, a vibration strength (K) is adopted to characterize the intensity of mechanical vibration [19]. K is a dimensionless parameter defined as the ratio of acceleration of vibration to that of gravity:

$$K = A(2\pi f)^2/g \tag{1}$$

2.3. Experimental procedure

For drying experiments, when the effect of one parameter was being examined, the values of the other parameters were held constant. The lignite particles were non-spherical (sphericity = 0.6, aspect ratio = 1.3), thus obtaining their minimum fluidization velocity from models was difficult. In this study, the minimum fluidization velocity was experimentally determined according to the usual method, i.e., as the point of intersection between the fixed regime and the fluidized regime. Similar to the previous studies [37,38], the minimum fluidization velocity (U_{mf}) required to the 1–3 mm lignite particles was approximately 0.58 m/s at ambient temperature. When increasing air temperature and particle size, the U_{mf} value of particles increased. Therefore, lignite particles were performed with air velocities form $1.5 \times U_{mf}$ to $2.2 \times U_{mf}$ to ensure all particles fluidization for all the experimental conditions (air temperatures from 120 to 200 °C). The whole experimental conditions and particle physical properties are listed in Table 2.

Drying was continued at time steps of 15 seconds, reaching equilibrium moisture under experimental conditions. Every 15 seconds, dried material was collected by a special sampler and this as-received material was immediately weighed. The moisture content values and the drying rate values were then calculated on a wet basis by means of the following equations, respectively.

$$\mathrm{MR} = \frac{W_{\mathrm{wet}} - W_{\mathrm{dry}}}{W_{\mathrm{wet}}}\left(\frac{g \ \ \mathrm{water}}{g \ \ \mathrm{wet\ \ coal}}\right) \tag{2}$$

$$R = \frac{(W_{\mathrm{wet}})_{t+dt} - (W_{\mathrm{wet}})_t}{W_{\mathrm{wet}} dt}\left[\frac{(g \ \ \mathrm{evaporation})}{(g \ \ \mathrm{wet\ \ coal})(\mathrm{sed})}\right] \tag{3}$$

where MR is moisture content, W_{wet} is initial sample mass, W_{dry} is the mass of the dry coal, R is the drying rate, dt is time steps and t is the drying time. To provide sufficient precision, all experiments were duplicated or triplicated under the same experimental conditions and the mean of several repetitions was adopted.

2.4. Kinetics modeling

The most common empirical thin layer drying equations (Table 3) were used to describe moisture transfer in the lignite. The correlation coefficient, R^2 was one of the primary criteria for selecting the best equation expressing the drying curves of the sample. In addition to R^2, the various statistical parameters such as root mean square error (RMSE), chi-square χ^2, and the F-value were also used to evaluate the consistency of the fitting process. The higher values of R^2 and the F-value as well as the lower values of RMSE and χ^2 were the better model fitting [9]. These parameters were calculated from this statistical package based on the following equations:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp.i} - \mathrm{MR}_{\mathrm{pre}.i}\right)^2}{N}} \tag{4}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp.i} - \mathrm{MR}_{\mathrm{pre}.i}\right)^2}{N - p} \tag{5}$$

$$F\text{-value} = \frac{\mathrm{MS}_{\mathrm{treatment}}}{\mathrm{MS}_{\mathrm{error}}} \tag{6}$$

where MR_{exp} and MR_{pre} are experimental and predicted moisture ratio values, respectively, N is the number of observations and p is the number of constants in each set. $\mathrm{MS}_{treatment}$ is the mean squares for treatments and MS_{error} is the mean squares for error.

3. Results and discussion

In Figs. 2–9, the effects of the presence of vibration, inlet air temperature, superficial air velocity, particle size, vibration strength (frequency and amplitude) and bed height on the drying curves and drying rate are

Table 1
The proximate and ultimate analysis of Chinese lignite (in wt.%).

Moisture (ad)	Volatile matter (ad)	Ash (ad)	Fixed carbon (ad)	C (ad)	H (ad)	N (ad)	S (ad)	O (ad)
25.85	22.36	22.93	28.86	27.3	3.08	0.93	0.53	8.86

ad, air dried.