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Effect of storage time on the flowability of biomass-coal granular system

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ABSTRACT

The influence of storage time on the flowability of biomass-coal blends is experimental and theoretical investigated. The results show that there exists exponential relationship between discharge rate and storage time in an appropriate rice straw mass fraction range (less than 10%). In addition, the mechanism of gravity discharge rate variation for biomass-coal blends is theoretically investigated by analyzing the porosity variation of particle bed. The mechanism of porosity variation in the binary granular system is theoretically analyzed on the basis of emergent gas, mutual compression and particle rearrangement, and a mathematical model has been developed which agrees well with the experimental results. Furthermore, relaxation effect is proposed, which is mainly induced by elasticity of rice straw particle and cohesion of blends. Relaxation time is the most important parameters determining this effect. The latter decreases with increasing of coal particle size and biomass mass fraction.

1. Introduction

The powder storage is of importance in many industrial processes and has lots of applications in food, agriculture and chemical [1–5]. It is well known that the granular flowability becomes more or less incapable of flowing out over a longer storage time in silo. Notably, powder flowability is a major issue for handling and processing of bulk solids. Therefore, it must be sensible and necessary for the study of the influence of storage time on the blends flow characteristics.

To make better co-utilization of biomass-coal blends, it is crucial to investigate its flow characteristics. There have been quite a few studies on characterizing flowability of pulverized coal [6–8] but few for biomass fuels. Due to biomass substance construction and anisotropic in spatial structure, biomass particle differs from other granules in the field of storage, transport and mixing. For biomass particles, the shape and particle size distribution have been established [9]. Nehru et al. [10,11] have conducted to study the compaction characteristics and shear strength of several kinds of typical biomass. Recently, due to the occurrence of intermittent flow or arching behavior, Miccio [12] and Barletta [13] carried out experiments to explore the biomass blockage, which provides a significant theoretical fundamental for the design of storage units containing biomass solids. Besides, a model has been proposed to depict the mechanisms of biomass blockage during screw feeding [14]. For biomass-coal blends, only limited literatures have been studied its flow properties. Zulfiqar and Moghtaderi 15] found that blending coal with sawdust reduced the likelihood of flow stoppage because sawdust particles lowered the cohesive strength. Similarly, the flowability of biomass-coal mixtures was studied by shear tests [16]. The results showed that the addition of biomass could not generate negatively influence on the reliability of the handing operations during the industrial process when the biomass mass fraction less than 20%. The milling characteristics of biomass-coal blends have been researched by Elham et al. [17]. This work has a wide practical application in co-firing and co-gasification of biomass-coal blends.

Many common phenomena, such as caking, deliquescence and deterioration, occur due to storage time, which contributes to the reduction of granular flowability. Some recent investigations [18,19] have researched the time-dependent flow characteristics of granular materials. In order to demonstrate the relation between storage times and flow behavior of shredded grain products, flow-function values were determined through shear tests by Fürll et al. [1]. The results show that the flow behaviors decrease with the increasing of storage time. Changes on any one storage condition variable, including storage time, relative humidity, temperature, etc., have an effect on the flowability of bulk solids to a certain degree, just as proved by some authors [10,18,19]. Previous researchers focused on the qualitative description about the flow behavior and how it is influenced by storage time. To date, there are few reports on the flowability of biomass and coal blends. Furthermore, there is no mathematical model involving the relation between gravity discharge rate and storage time.

In view of the importance of biomass-coal blends flowability for the success of blends co-gasification, some of the laboratory scale data and findings have already been published by our group [9,20,21]. Motivated by the studies cited above, we carried out further study on the influence of storage time on gravity discharge rate for biomass-coal blends. The

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Nomenclature

d_p	mean particle Sauter diameter, μm
ρ_s	particle density, kg/m^3
D_0	outlet diameter, mm
Q	air volume per unit time, m^3/s
k	permeability, mm^2
A	cross-sectional area of powder bed, mm^2
ΔP	pressure drop across solid bed, Pa
L	length of powder bed, mm
q	airflow rate, mm/s
W	gravity discharge rate, g/s
W_t	gravity discharge rate after storage time, g/s
C_∞	the cohesion strength at steady state, kPa
M_i	a series of constant
W_∞	gravity discharge rate at steady state, g/s
ΔW	variation of discharge rate, g/s
ρ_b	bulk density, kg/m^3
ρ_∞	bulk density after compression, kg/m^3
t	storage time, s
C	cohesion strength between particles, kPa
k_1	the slope of the model, g/s

Greek letters

w	rice straw mass fraction, %
ε	porosity of blends
ε_t	porosity of blends after a period of storage time
ε_∞	porosity of blends at steady state
μ	gas viscosity, Pa · s
ε_0	porosity of blends
ε_b	bulk porosity
$\Delta\varepsilon$	variation of porosity
τ_1	the relaxation time of blends, s
τ_2	the relaxation time of blends, s

purpose of this paper is to investigate the influence of storage time on the flow characteristics of biomass-coal blends, aiming to quantify the relationship between gravity discharge rate and storage time. Therefore, a model is presented which can be quantitatively analyzed the relationship between the discharge rate and the storage time for biomass-coal blends. Furthermore, we believe that this paper would provide theory foundation to the flowability of mixed granular system, and it will be useful in more chemical industrial processes.

2. Experimental

2.1. Materials

Shenfu bituminous coal and a kind of representative biomass (rice straw) are used in this study, and their physical properties are shown in Table 1. Fig. 1(a) shows the cumulative particle size distribution functions of Shenfu bituminous coal, which is measured by a particle size analyzer of Malvern Mastersizer 2000. The cumulative particle size distribution function of rice straw, measured with a particle image analyzer of BT-2900, is illustrated in Fig. 1(b). The particle size distribution (PSD) results of all powders with data relevant to the spread of the PSD are illustrated in Table 2. Since the moisture content is a key factor to the flow properties of powder [22,23], the moisture content of experimental material measured by an infrared moisture meter MA150 is controlled below 2%. In the experiments, mixtures with a high mass fraction of biomass (exceeds 15%) prove to be incapable of flowing out from the hopper over a period of storage time. Thus, rice straw particle maximum mass fraction is 10% in the study.

2.2. Apparatus and methods

The experimental apparatus mainly consists of four parts: transparent perspex hopper, receiver vessel, digital scale and baffle as shown in Fig. 2(a), and its dimensions are given in Fig. 2(b). Experiments are performed at room temperature and atmospheric pressure. To obtain high accuracy experimental data, it should be noted that each discharge rate presented in this paper represents an average value of seven runs. The effect of instrument error in the measurements on the discharge data is thus minimized due to the digital scale and stopwatch with sensitivities of 0.1 g and 0.01 s, respectively. To obtain the relationship between discharge rate and storage time, a comprehensive series of experiments are performed by six storage times (10 s, 30 s, 60 s, 120 s, 600 s and 1800 s) on several kinds of mixtures. The detailed results have been summarized in Table 3. A high-speed camera (Fastcam APX-RS) combined with a continuous 2000 W halogen spot is used to capture change of bed level during the storage process. Furthermore, rheology properties (cohesion and permeability) are measured by FT4 rheometer in this study. The cohesion is defined as the intercept of the Jenike yield locus with the vertical axis during the shear test. Permeability is a measure of how easily material can transmit a fluid (in this case air) through its bulk. Data from permeability test are usually represented as pressure drop across the powder bed versus normal stress for a constant air velocity. The lower pressure drop is equivalent to higher permeability.

3. Theoretical analysis

3.1. Model assumption

Porosity is an important parameter in granular gravity flow. For biomass-coal blends, as storage time increases, the porosity is gradually diminished along with gravity discharge rate. In view of the important relationship between porosity of powder bed and gravity flow rate, we can assume that the ratio between variation of discharge and variation of porosity is constant.

3.2. Supportive experimental tests

For incompressible powder, with the increase of storage time, the porosity and the gravity discharge rates are nearly constant. Thus, to

Table 1
Material properties.

Material	Sample number	Moisture content (%)	ρ_b (kg·m^{-3})	Average length (μm)	Average width (μm)	Average aspect ratio
Coal	a	1.92	607			
	b	1.3	651			
	c	0.84	681			
Rice straw	I	1.28	222	206	97	2.25
	II	1.36	200	465	145	3.64
	III	1.06	190	2415	384	8.22