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An investigation of the effect of particle size on discharge behavior of pulverized coal

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ABSTRACT

In this paper, pulverized coal from industry was used as the experimental material. In order to study the effect of particle size, the pulverized coal was sieved into seven samples with different particle sizes. Firstly, the material properties as packing, incipient flow and wall friction properties were evaluated. Meanwhile, a transparent Perspex hopper was used to monitor the change of discharge behavior of pulverized coal caused by the increase of particle size. From the visual observation of discharge test, a progressive transition from blocking to unstable flow and to mass flow was found as the particle size increased. Hence, a complete set of physically based equations for compressibility, flowability and powder consolidation has been derived. Then, a new method, taking into account the stress state in the hopper, is introduced to assess the discharge behaviors of pulverized coal. The validity of this new method has been confirmed by comparing theoretical and experimental discharge behavior for pulverized coals. The theoretical approach based on stress state analysis, is able to provide results which correlate well with the experiments.

1. Introduction

Entrained-flow pressurized gasification process of pulverized coal, including the storage, discharge and conveying of pulverized coals, is one of the best contemporary coal gasification technologies [1,2]. However, there are several well-known problems in the handling and storage of pulverize coal, such as bridging, channeling, fluctuating flow rate or even blocking in processing equipment and storage, as the tendency of agglomeration caused by strong inter-particle forces [3–5]. The most common and serious problem is no-flow, due to arching or ratholing [6,7]. Thus, reliable information of flow properties of the pulverized coal concerned is required for reliable flow from the hopper, which is essentially crucial in handling and processing operations [8,9].

Flowing or yielding means that a powder is brought to irreversible deformation, which can be caused by an external mechanical stressing event. This stress can be produced by either force or energy. According to this method, only the trouble-free discharge of a powder out off a hopper by its dead weight is considered as good flowability. In contrast, powders that show flow problems are classified as poorly flowing or non-flowing.

It is well known that there are two flow patterns in hopper or bins: mass flow and funnel flow, and most flow problems are associated with the funnel flow pattern [10,11]. To avoid funnel flow, it is important to determine properties of pulverized coal. One of the major factors affecting flow patterns is particle size. In the case of powder with particle size less than 100 μm, van der Waals based interparticle forces, exceed the gravitational force by several orders of magnitude [12–14].

Thus, flow problems are very common in the case of cohesive powders with particle sizes less than 100 μm. To avoid this technical problem and hazard, it is really necessary to understand the effect of particle size on flow properties of pulverized coal. In order to improve a reliable and controllable discharge of powder from hoppers, effects have been taken to develop a proper method for discharge behavior of pulverized coal prediction.

Powder flow characteristics are often investigated adopting a variety of methods. One of the most common of those is the shear test [15–17]. Using Mohr's circle analysis, various important parameters may be extracted from these results. These properties include the major Principal stress, the minor Principal stress, the unconfined yield stress, the cohesive, the angle of internal friction and the effective angle of internal friction. In previous studies, Jenike applied two-dimensional stress analysis to develop a numerical methodology to determine the minimum hopper slope required for mass flow and the minimum outlet dimension for unobstructed gravity flow [18]. Although this method has been widely used over the past few decades, it occasionally gives irrational results, due to the assumption of constant average material properties [19]. In fact, some of the properties, such as effective angle of internal friction and bulk density, are functions of stress state.

To overcome this matter, a complete set of physically based equations for compressibility, flowability and powder consolidation

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are used in this study. And, a new approach is introduced to assess the discharge behavior for the pulverized coal. As opposed to the original Jenike criterion which only considers constant average material properties, the new method considers the effect of stress state on material properties by using these physically based equations. The validity of the new theoretical approach will be examined by comparing the theoretical findings and experimental discharge behavior.

2. Materials and methods

2.1. Materials

The initial material for this study is industrial bituminous pulverized coal having a particle density of 1490 kg/m^3. The initial material is sieved by an electric vibrating screen. Seven samples of pulverized coal were obtained. The physical properties of these samples are reported in Table 1 and Fig. 1.

The particle size distribution of the pulverized coal in the experiments can be described using the Rosin–Rammler distribution function [20,21]. The general expression of the Rosin–Rammler function is:

$$R(D) = 100 - \phi = 100\exp\left[-\left(\frac{D}{D_e}\right)^n\right] \quad (1)$$

where $R(D)$ is the distribution function, D is the particle size, D_e is the mean particle size and n is a measure of the spread of particle size the large value of which designates a narrower size range.

This expression can be rewritten as:

$$\lg\{\lg[100/R(D)]\} = n \cdot \lg D + M_1 \quad (2)$$

where M_1 is a constant. A plot of lg$D$ versus lg(lg(100 / $R(D)$)) will result in a straight line of slope n if the behavior of the material fits the RR model. From the observation of Fig. 2 and the corresponding linear correlation coefficient, one deduces that the RR model provides a perfect fit to the experimental PSD curve. As shown in Table 1, the samples have approximate n within the range of 0.9–1.2, indicating the same level of size range. Therefore, the particle size represents the major factor for this study.

2.2. Experimental

2.2.1. Compressibility test

Compressibility is a measurement of how density changes as a function of applied normal stresses. The sample vessel specification is 50 mm × 85 ml. The measurement utilizes a vented piston to compress the sample under the increasing normal stress. Prior to each measurement, the sample was first prepared by conditioning and splitting using the standard FT4 blade and split vessel assembly to remove any residual compaction and build a uniform and loose condition in the bed of powders. After the preconditioning and slitting procedure, a sample of 85 ml is left behind and the condition bulk density ρ_{CBD} is obtained. Before the compression occurs, the blade is then exchanged for the vented piston. Fig. 3 shows the schematic of the compressibility test; each normal stress will be applied for a defined time to allow the powder to reach equilibrium. The distance traveled by the piston is measured for each applied normal stress and the bulk density is automatically calculated.

Table 1
Physical property and packing properties of all pulverized coals used in this study.

Materials	d_v (μm)	n	ρ_{CBD} (kg/m^3)	$\rho_{b,0}$ (kg/m^3)	$\sigma_{z,0}$ (Pa)	N
a	223.8	0.91	739.0	742.4	3863.0	0.022
b	141.3	1.02	723.0	722.1	1475.2	0.023
c	94.2	1.11	690.6	691.2	1208.7	0.025
d	74.9	1.12	642.3	629.9	347.3	0.028
e	55.9	1.21	621.9	605.6	289.0	0.031
f	43.2	1.27	584.3	576.2	458.1	0.040
g	17.7	1.21	520.5	439.7	43.4	0.058

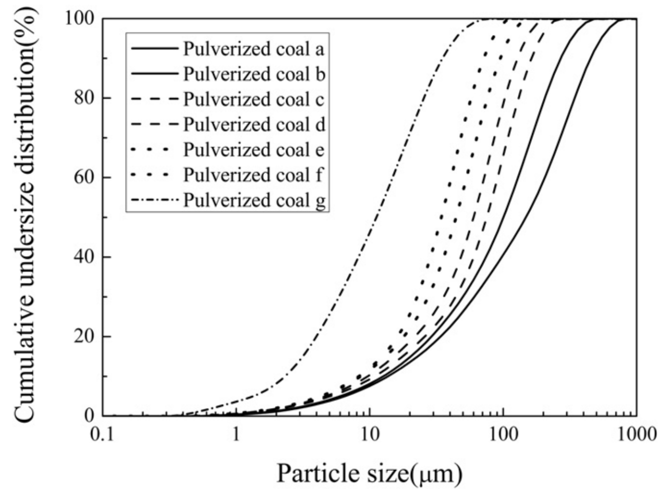

Fig. 1. Cumulative particle size distribution of the samples obtained with laser diffraction (Malvern 2000).

2.2.2. Shear cell and wall friction test

A rotational shear cell is used to quantify the incipient flow behaviors of the pulverized coals. This shear cell consists of a vessel containing the samples and a shear head to introduce both vertical and rotational stresses, as shown in Fig. 4(a). After completion of one conditional cycle, a vented piston is used to induce a precise consolidation stress in the sample. The pre-consolidation procedure is carried out prior to the splitting procedure to ensure that the sample is consolidated. Then, the vessel was split. To ensure that the surface of the sample is suitably consolidated, the sample is recompressed by the shear cell head to remove any disturbances caused by the split. After the previous operations are done, the shearing sequence could begin. Based on the normal and shear stress collected, the yield locus at a given pre-consolidation condition can be acquired.

Fig. 5(a) is a typical σ–τ diagram, showing two Mohr circles, yield locus, and effective yield locus. With these terms, the angle of internal friction φ_i, effective angle of internal friction φ_e, cohesive C, major Principal stress σ_1, minor Principal stress σ_2 and unconfined yield stress

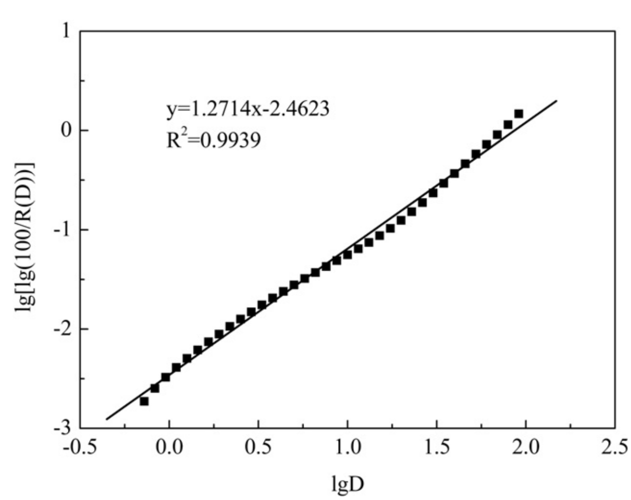

Fig. 2. Relationship between lg{lg[100/R(D)]} and lg$D$ of pulverized coal (d_v = 43.2 μm).