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Method for evaluating packing condition of particles in coal water slurry

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ABSTRACT

In the coal water slurry (CWS) industry, it is essential to achieve high packing density of product particles in order to obtain a high concentration without affecting the flowability. In this study, a method based on an index *E* is proposed for evaluating the packing density of particles in CWS with given particle size distribution (PSD) and tested on bituminous and lignite coal. These two types of coal were ground and mixed in different proportions to obtain different packing densities. The experimental results show that the CWS concentration increased with *E*, implying the good applicability of the proposed method. By calculating *E* for different PSDs, it was found that the packing got closest when the parameters in Rosin–Rammler equation and Alfred equation were 0.75–0.85 and ~0.5, respectively. In addition, the packing density for unimodal PSD is generally lower than that for multimodal PSD. In contrast, the average sizes of the mixed samples did not affect the packing status in CWS and the product concentration consistently. With some adjustments, the proposed method can also be used to evaluate the tapped packing density of dry coal powders, with some applicability.

1. Introduction

The packing density is a parameter that is commonly used to describe the packing condition of particles. It is an important index that is used to characterize many powder products or suspensions such as pharmaceuticals, composite materials, coal water slurry (CWS), and concrete. CWS is a kind of slurry fuel mixed with coal powder, water and small quantities of dispersant, and has been studied for decades since the Oil Crisis in 1970s as a replacement for fuel oil in boilers for power generation and industrial heating [1]. In China, the development of CWS has become one of the research focuses of clean coal technology. In the CWS industry, high packing density always leads to high concentration (high calorific value) at required flowability without other high-energy consumption processes, such as thermal upgrading [2,3].

In the last few decades, several models have been developed to predict the packing density of materials under given conditions (size distribution, density, sphericity, etc.). Furnas [4] and Westman et al. [5,6] conducted the earliest studies on systematically describing the packing conditions of mixed particles with different sizes; they mainly focused on the packing behavior of discrete-sized particles with large size differences. However, in practice, it is more important to describe the packing condition of nonspherical particles with continuous size distribution. Andreasen [7] was the first to study the packing behavior of continuous size distribution powders; he used the Gaudin–Schuhmann (G–S) equation to describe the real particle size distribution (PSD):

$$F(d) = 100 \times \left(\frac{d}{D_{\max}}\right)^{\beta}, \% \quad (1)$$

where d is the particle size, $F(d)$ is the cumulative mass content of particles finer than d; $D_{\max}$, the size of the largest particle; β, the characteristic parameters. And he found that the packing system tended to show relatively higher packing density when β was 0.3–0.5. Funk and Dinger [8] introduced the minimum particle size to G–S equation:

$$F(d) = \frac{d^{\beta} - D_{\min}^{\beta}}{D_{\max}^{\beta} - D_{\min}^{\beta}} \times 100, \% \quad (2)$$

where $D_{\min}$ is the size of the smallest particle. This modified equation was called Alfred equation. Through a computer simulation, they found that the system had the closet packing when β was 0.37. Suzuki et al. [9–11] derived a theoretical equation for the relationship between the average coordination number and the void fraction, and they obtained a result different from that in Andreasen's study, indicating that β should be 0.5–0.8 if dense packing is required. In the concrete industry, the Fuller curve [12] is a well-known method for evaluating the packing condition of concrete's PSD. However, the packing density could not be directly obtained using Fuller's method.

Stovall derived the “linear packing density model”, the most frequently used model for predicting the dry particle packing density, using two parameters representing the loose effect and wall effect [13]. Yu et al. [14–18] expanded the model to evaluate the packing of

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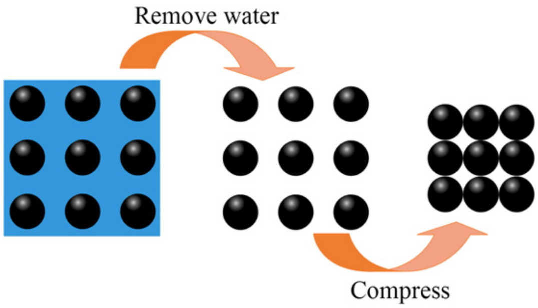

Fig. 1. Imaginary pretreatment.

nonspherical particles by using the concept of equivalent packing diameter. De Larrard [19] improved Stovall's model and derived the "compressible packing model" with a new parameter to represent the difference between the theoretical and actual packing. Kwan et al. [20] improved Stovall's and Yu's models by adding a new parameter representing the "wedging effect" and derived a three-parameter model. Chan [21] tested these three models and found that the three-parameter model was more accurate. However, these abovementioned parameters are commonly different for various materials, making it difficult to apply these models.

Since 1960s, various computer simulation algorithms have been proposed to simulate the particles packing [22–28]. These methods provided a clear insight to the particle interaction behavior and could help in studying the packing phenomenon. However, they required advanced hardware, complex designs, incurred long calculation times and high costs.

Fewer studies have focused on particle packing in slurry than in dry powders. Funk employed his studies on packing density of dry powders [29,30] to CWS preparation and got the US patent [31]. Zhang [2,32] derived a so-called "compartment packing method" for CWS preparation, and obtained the same result with Funk's studies [8] through mathematical analysis. In addition, Zhang pointed out that the difference between Funk's [8] and Suzuki's studies [9–11] was caused by the size difference between their study subjects. Zhang also studied the packing density of PSD governed by Rosin–Rammler (R–R) equation:

$$F(d) = 100 - 100\,\mathrm{EXP}\left[-\left(\frac{d}{dx}\right)^{\alpha}\right], \% \tag{3}$$

where α is the characteristic parameters whose value affects the shape of the PSD curve, and dx is the characteristic size whose value affects the apparent size of the packing system and equals the size value when $F(d) = 63.21\%$. He indicated that the packing got closest when α was 0.7–0.8.

Based on Zhang's achievement, an improved approach for evaluating the packing condition of particles in CWS is proposed in this study. The following discussion indicates that our method is much simpler than abovementioned models.

2. Model description

2.1. Simplification

Because of the surface forces as the Van der Waals force, electrostatic repulsion, and mechanical barrier force of hydration shell [2,33], particles in CWS behave quite differently from dry coal powders, mainly in the following respects:

(1) Under stable conditions, particles could not touch each other directly owing to the water among particles. Therefore, the particles are movable in a specific path depending on the packing condition, concentration and compressibility of the water layer.
(2) The particles' spatial distribution is more uniform than in dry powders because of the shearing process.
(3) The entire system is flowable and deformable. As a result, the packing density does not change when the CWS is evenly divided into parts unless some components are removed from the system.

Therefore, packing in slurry could be simplified as follows: the three abovementioned effects in dry powders packing could be unified by a loose effect that, in turn, could be simplified as the voidage expansion of the self-packing of coarse particles.

2.2. Modeling

Based on the above-described analysis, the following assumptions were made in our model to simplify the calculation for packing condition:

(1) Particles are nonporous and spatially uniformly distributed.
(2) The entire system could be divided into a limit number of microclusters, each of which has the same packing mode and PSD as the system.
(3) Microclusters could be deformed, reorganized and repacked artificially without changing the packing density.

The water among the particles is removed imaginarily, and the packing system is compressed without changing the particles' relative position, as shown in Fig. 1. First, the particles are divided into n narrow grades by particle sizes. $D_{\max}$ is the size of the largest particle in the system; S, the size ratio of neighboring size grades (coarse to fine); V_i, the volumetric fraction of the ith grade (%); ε_i, the self-packing voidage of the ith grade; d_i, the ceiling size of the ith grade (μm). Therefore, $d_n = D_{\max}$, $d_1 = D_{\max}/S^{n-1}$, $d_i = D_{\max}/S^{n-i}$ and $\sum_i^n V_i = 100\%$.

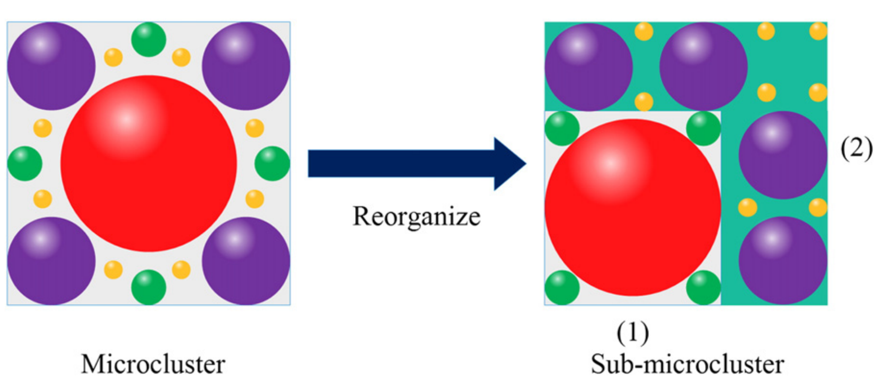

Fig. 2. Model simplifying process.