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Optimization of packing state in brown coal water slurry based on the two-grade fractal model

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ABSTRACT

A newly designed two-grade fractal model for improving the packing state in brown coal water slurry (BCWS), which was built on the fractal theory and modified by separating the size into two grades, was investigated systematically. Packing efficiency (PE) and regression levels of the fractal model in various particle systems were analyzed. The results showed that the PE of brown coal particle system is determined mainly by the fractal characteristics of particles under 74 μm and the packing state in BCWS can be significantly improved when the fractal dimension is around 2.6–2.7. In addition, the two-grade fractal model fits the PSDs for various particle systems with different graduation ratios of coarse samples (CS), fine samples (FS) and ultra-fine samples (UFS) well. PE reaches the maximum value when the graduation ratio is 7:0:3 (CS:FS:UFS) and the fractal dimension is 2.7080, which is consistent with the calculated results. It was confirmed by the slurry preparation experiment that the maximum solid loading of BCWS increased by 2.9% through optimizing the packing state using two-grade fractal model.

1. Introduction

Coal water slurry (CWS), a homogeneous solid–liquid system with pseudo-plastic or Bingham properties, is generally composed of 60–75% coal, 25–40% water and 1% chemical additives chemical additives [1–3]. CWS showed good performance in burning processes, gasification processes and coal-to-liquid processes because of its good fluidity [4].

Over the past several decades, the rate of discovery of high rank coals like bituminous coal and hard coal has consistently lagged behind the rate of world consumption and the future availability of such resources has become a serious concern. Therefore, the less desirable low rank coals especially lignite has come to the force as important resources [5]. Although the low rank coals has extremely high moisture content (25–60%), which causes serious problems like decreasing the grindability of brown coal and the content of free water as the flowing media in making CWS, they are accessible and available in abundance [6].

The solid loading of CWS is mainly determined by physical & chemical characteristics of coal samples, properties of dispersants and PSD [7]. Techniques like hot oil immersion drying, hydrothermal dewatering, microwave irradiation, solvent/hot water treatment and impregnated with molasses have been employed to upgrade lignite. Through these processes, changes like collapse and shrinkage of pore structures, decrease of the contents of oxygen-functional groups and increase of the value of C/O happened, resulting in the increase of coal loading of CWS [4,8–14]. One anionic dispersant (calcium lignosulfonate) was proved to be effective in increasing the free water content and reducing the bound water content [15]. In addition, preparation, molecular structure and mechanism of some new CWS additives, such as bamboo pulp lignin-based efficient dispersant, polyacrylic acid series and modified sodium lignin sulfonate, were studied [16–18].

Both the techniques of lignite upgrading and the development of new reagents are quite complicated and economically unfeasible. However, increasing the PE of coal particle system through optimizing the PSD serves as an effective method to significantly improve the properties of slurry because of its economic feasibility, simple craft and good applicability [19].

Originally, the PSD for particles in CWS was described with the R-R model

$$R(d) = 1 - e^{[-(d/d_M)]^n} \tag{1}$$

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where $R(d)$ denotes the cumulative content under size, d denotes the particle size, d_M is the particle size when the cumulative content under size is 73.2% and n is the parameter of this model [20].

R-R model is a classical model to guide grinding as well as graduation in CWS process. Compared with Alfred model, the change of Rosin–Rammler system's PE caused by the fluctuation of parameter n is much less obvious. As a result, though the PE of Rosin–Rammler model is lower than that of Alfred model, Rosin–Rammler model is more suitable for application in making CWS with high rank coals [21]. Lignite is known to be a low rank coal with high inherent moisture content, which leads to the decrease of the free water in the CWS system, thereby diminishing solid loading of CWS. Therefore, to make high solid concentration CWS with lignite, a new model which is able to increase the PE of a particle system should be put forward.

2. Model description

2.1. Calculation of PE

The PE of a particle system in CWS is difficult to obtain with experimental methods for the existence of water and the different packing state between particles in the CWS and dry particles [21]. In general, PE is calculated according to the skipped-grade packing model proposed by Rongzeng Zhang, which describes the packing state of coal particles in CWS definitely. This model is in the form of

$$PE = \frac{100}{\sum_{i=n-m+1}^{n} \frac{V_i}{1-\max\{\varepsilon_i, \varepsilon_i^*\}}}, \ \% \tag{2}$$

where V_i is the volume percentage of ith grade, n denotes the number of grades, m is the number of grades that skipped, ε_i denotes the self-packing voidage of ith grade and ε_i^* is the required voidage of ith grade [22].

2.2. Fractal theory

Fractal theory studies on the irregular geometries and describes graphs, phenomenon and principles with self-similarity [23]. In recent years, fractal theory has been used in areas like analysis of adsorption-induced matrix deformation on coalbed methane transport, definition of raceway boundary, simulation for permeability of porous media and classifying dynamic textures and so on, which has obtained favorable results[24–27]. Fractal objects follow the scaling law which is shown as

$$M(L) \sim L^{D_f} \tag{3}$$

where $M(L)$ denotes the measurement of fractal object such as the length of a line, the area of a surface and the volume of an object, L denotes the length scales and D_f is the fractal dimension [28]. Additionally, D_f can be calculated using the following equation,

$$D_f = \frac{\lg[N(1/\gamma)]}{\lg(1/\gamma)} \tag{4}$$

where γ is the linear similarity ratio and N is the number of measurements under one value of γ [29,30].

Eq. (4) can be transformed into

$$N(x) = N(x_{\max})(x/x_{\max})^{-D_f} \tag{5}$$

where x and $x_{\max}$ denote the length scale and the maximum length scale of fractal materials separately while $N(x)$ and $N(x_{\max})$ are the measurements of materials with length scales of x and $x_{\max}$ respectively.

2.3. Fractal model of PSD for particles in CWS

CWS is a multistage and compound fuel system with composite microcosmic structure. The particles in CWS are a self-similar system and the PSD for coal particles can be described with the fractal theory. The process of filling the space with different grades of coal particles in CWS resembles structuring Sierpinski sponge by removing regular hexahedrons.

To apply fractal theory into continuous case, both sides of Eq. (5) are differentiated and the number of coal particles with size ranging from x to $x + dx$ is

$$-dN = N(x_{\max})D_f x_{\max}^{D_f} x^{-(D_f+1)} dx \tag{6}$$

Then the mass of coal particles with size ranging from x to $x + dx$ is

$$\begin{aligned} dM &= \rho k_V x^3(-dN) \\ &= k_V N(x_{\max})D_f x_{\max}^{D_f} x^{2-D_f} dx \end{aligned} \tag{7}$$

where ρ is the true density of the coal sample and k_V denotes the volume coefficient based on dimensional analysis.

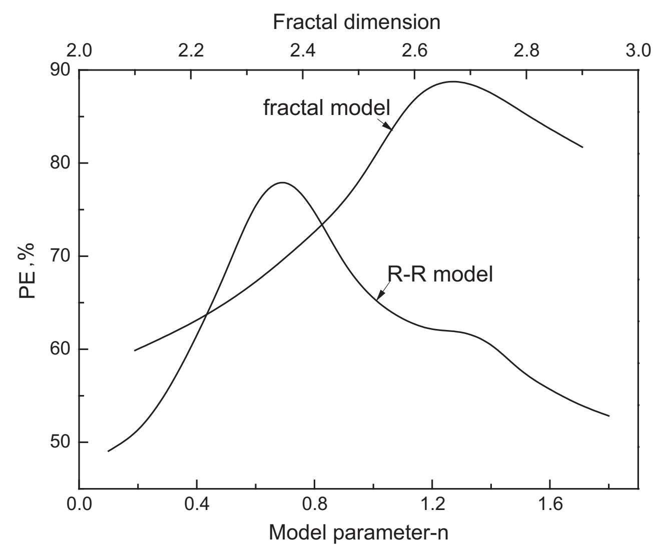

Fig. 1. Effect of parameters on the PE of particle systems using fractal model and R-R model.

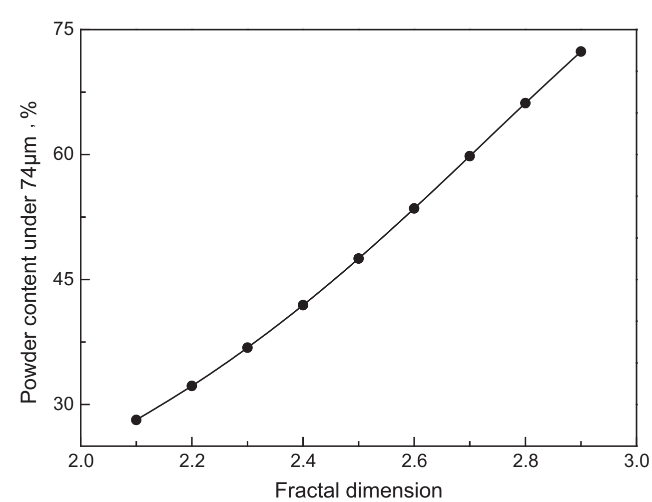

Fig. 2. Contents of particles under 74 μm with different values of fractal dimension.