Powder Technology 254 (2014) 548–555

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

# Force characteristic of the large coal particle moving in a dense medium gas–solid fluidized bed

Jingfeng He *, Yuemin Zhao *, Yaqun He, Zhenfu Luo, Chenlong Duan *

School of Chemical Engineering and Technology, China University of Mining and Technology, Xuzhou 221116, China

ARTICLE INFO

*Article history:*
Received 21 September 2013
Received in revised form 27 December 2013
Accepted 24 January 2014
Available online 3 February 2014

*Keywords:*
Force characteristic
Dense medium gas–solid fluidized bed
Numerical simulation
Spectral analysis

ABSTRACT

Force characteristic of the large coal particle was investigated when it moved in a dense medium gas–solid fluidized bed with the 100–300 μm Geldart B magnetite powder as fluidized medium. We selected two groups of coal particles with the equivalent diameters of 13 and 25 mm as the studying objects. The theoretical force calculation model of the large coal particle was established by force analysis. The approaches of experimental measurement and numerical simulation were combined to determine the force characteristic of the large coal particle. The results indicate that the forces vary within certain suitable ranges and present uniform fluctuations when the dense medium gas–solid fluidized bed maintains a stable fluidization state. The spectral analysis method was introduced to compare the force results of measurement and simulation. Finally, we obtain the conclusion that the theoretical force calculation results provide good agreements with the measurement and simulation results, which also validates the accuracy of the measurement results and the reliability of the simulation results for the force characteristic of the large coal particle.



## 1. Introduction

The coal beneficiation technology applying the dense medium gas–solid fluidized bed as a major separator has been developed and promoted since 30 years ago [1–13]. Being compared with the wet beneficiation technology of coal, this technology has some advantages of lower investment, modularized system, without any water circulation system, less environmental pollution and lower operating cost. Therefore, it has a large application potential to be widely developed and utilized in the areas and countries with abound coal resources but water shortage, such as the middle and west regions of China, Midwest regions of the USA, South Africa, southeast regions of India and so on [14]. As the major equipment of the technology, the dense medium gas–solid fluidized bed has been a focused studying object by a number of scientific researchers in recent years [15]. Through some special flow properties and the interactions between the gas and fluidized medium phase, the dense medium gas–solid fluidized bed could provide a stable fluidization state and favorable environment of the density distribution for coal beneficiation. Then, the feedstock stratifies by bed density, with the lighter particles (cleaning coal) floating and the denser particles (tailings) sinking based on the Archimedes' theorems [16]. Hence, it is significantly necessary to pay more attention to the force characteristic of large feeding coal particle moving in the dense medium gas–solid fluidized bed, which determines the dynamical behavior and separation performance of the large coal particles with different physical properties.

Kunii and Levenspiel, Rios, Lim and Agarwal, Rees, Nguyen and Grace, Hoffmann, Soria-Verdugo, Daniels, and Wei et al. have carried out a few researches on the dynamical behaviors of the large immersed particle and the movement behavior and distribution characteristic of the fine particles of fluidized medium with different approaches [17–26]. Especially, Zhang Q. has proposed the Particle Measurement Sensor (PMS) based on three-dimensional (3D) acceleration sensing, which is an intelligent particle spy capable of detecting, transferring and storing data. This technology could be widely applied in the field of fluidization system [27]. In the previous study, our group has made progresses in the force measurement and simulation of the large immersed particle in a dense gas–solid fluidized bed [28]. We used three spherical steel balls with different diameters as studying objects and selected the coarse-sand particles and fine-glass powders as fluidized mediums, respectively. The previous studying results provide the foundational achievements for the further research. However, based on the previous achievements, we still need to focus on the force characteristic of the actual coal particles and utilize Geldart B magnetite powder as the fluidized medium, which are corresponding with the practical application in the coal beneficiation field. Therefore, we have conducted further experimental and simulation researches on two groups of large coal particles in order to provide the basic dynamical achievements for studying the complex separation performance of coal particles in a dense medium gas–solid fluidized bed by bed density.

* Corresponding authors.
*E-mail address:* jfhe@cumt.edu.cn (J. He).

0032-5910/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.powtec.2014.01.072

## 2. Experimental, calculation and simulation

### 2.1. Experimental

The same experimental measurement system as introduced in the previous work was still applied to carry out the force measurements of large coal particles in the dense medium gas–solid fluidized bed [28]. Its diagram is shown in Fig. 1. A cylindrical fluidized bed with the diameter of 90 mm and height of 280 mm was designed as a major apparatus using the acrylic glass. A force sensor is installed above the top position of the fluidized bed with the measurement direction always along the direction of bed height. A coal particle is connected with the force sensor through a flexible line. The flexible line refers to the connecting line without any elasticity between the sensor and coal particle, which only plays a connecting role and doesn't exert its own effort on the coal particle. The connecting direction of the force sensor and coal particle is along the direction of bed height as well. The fixed method of the force sensor and its connecting approach with the coal particle could ensure the reliability of force measurement and avoid the influence of fixed method and the difference of orientation on force measurement. In addition, the results of the exploratory tests show that the measurement forces of different particles with a size range of 10–25 mm mainly distributed in the range of 0–10 mN. Therefore, the force sensor with the measurement range of 0–10mN was selected as the basic device to be applied in the formal force measurement experiments, which could ensure the accuracy of the force measurement as well. In addition, the large coal particles with the density of 1400 kg/m$^3$ were selected as the basic studying objects in this study, which belong to the cleaning coal among the raw coal. Initially, the fluidized medium is stacked in the bottom of the fluidized bed. Then, the medium is fluidized by starting to increase the gas velocity. The suitable gas velocity of the fluidized bed is determined by observing the bubbling performance and fluidization condition. The measurement results of pressure drop at different bed heights could be received and obtained dynamically and timely by the pressure sensor. By adjusting the gas velocity in a suitable range, the successive instantaneous forces of the large coal particle could be measured with the force sensor, and then the force data could be collected by a data receiver timely and displayed on a monitor with the special software, Strip Chart. Finally, we can obtain several groups of force data for one large coal particle with different gas velocities. Furthermore, the large coals with different particle sizes could be selected and the similar force measurement experiments could be conducted to obtain more results.

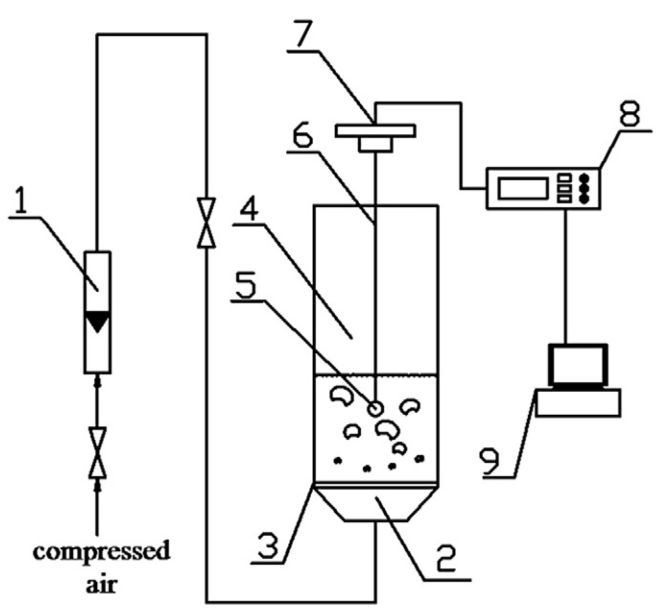


**Fig. 1.** Force measurement system of the large coal particle in a dense medium gas–solid fluidized bed. [1. gas flow meter; 2. air chamber; 3. gas distributor; 4. gas–solid fluidized bed; 5. large coal particle; 6. flexible line; 7. force sensor; 8. signal converter; 9. data receiver and monitor].

### 2.2. Calculation

The large coal particle is mainly subjected to its own gravity force $G$, buoyancy $F_B$, and drag force caused by fluid $F_D$ when it moves in the dense medium gas–solid fluidized bed. Therefore, the force balance equation of large coal particle in the fluidized bed could be calculated as Eq. (1).

$$\vec{F} = G + \overrightarrow{F_B} + \overrightarrow{F_D} \tag{1}$$

Besides, the mean density of the fluidized bed could be obtained by Eq. (2).

$$\rho_f = \frac{W}{A \cdot H} = (1-\varepsilon) \cdot \left(\rho_s - \rho_g\right) \approx (1-\varepsilon) \cdot \rho_s \tag{2}$$

Most of the coal particles are non-spherical with different shapes, so the particle shape should be considered in the force calculation. Thus, the degree of sphericity $\varphi_s$ and equivalent diameter of particle $d_e$ are selected as the basic parameters for the calculation of particle capacity. As a result, the buoyancy $F_B$ of the large coal particle could be calculated as Eq. (3).

$$F_B = \rho_f g V_p = (1-\varepsilon)\rho_s \cdot g \cdot \left(\frac{1}{6}\pi d_e^3\right) \tag{3}$$

The drag force $F_D$ caused by fluid in the fluidized bed could be solved as Eq. (4).

$$F_D = \frac{1}{8}\pi \cdot C_D d_e^2 \rho_f \left(u_f - u_p\right)^2 \tag{4}$$

Based on the previous achievements [29–34], when the large coal particle moves in the fluidized bed with a stable fluidization state, it could be obtained that the Reynolds number based on the diameter of the large coal particle is always lower than 1000. Thus, the drag coefficient $C_D$ could be represented as Eq. (5), which is also basically used for the drag coefficient between the gas and the bed particles in the simulation.

$$C_D = \frac{24}{Re}\left(1 + \frac{1}{6}Re^{2/3}\right) = \frac{24\mu}{\rho_f d_e \left(u_f - u_p\right)}\left[1 + \frac{1}{6}\left(\frac{\rho_f d_e \left(u_f - u_p\right)}{\mu}\right)^{2/3}\right] \tag{5}$$

Finally, the composite force $F$ of the large coal particle could be calculated and obtained as Eq. (6).

$$F = mg + (1-\varepsilon)\rho_s \cdot g \cdot \left(\frac{1}{6}\pi d_e^3\right) + 3\pi \cdot \mu d_e + \frac{1}{2}\pi \cdot \mu^{1/3} d_e \left[\rho_s d_e (1-\varepsilon) \cdot \left(u_f - u_p\right)\right]^{2/3} \tag{6}$$

It could be obtained from Eq. (6) that the composite force of large coal particle in the dense medium gas–solid fluidized bed is mainly determined by the weight and equivalent diameter of particles, the porosity of fluidized bed, the bulk density of fluidized medium, fluid viscosity, particle velocity, flow velocity, etc. In other words, the force of non-spherical particle in the fluidized bed is not only associated with its physical properties and moving velocity, but also related to the expanding characteristic of the fluidized bed and quasi-fluid property of fluidized medium after achieving stable fluidization. Therefore, it is