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Numerical studies of the influence of particles' size distribution characteristics on the gravity separation performance of Liquid-solid Fluidized Bed Separator

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ABSTRACT

A new CFD model for Liquid-solid Fluidized Bed Separator (LSFBS), namely the Eulerian-Eulerian-Lagrangian/RNG k-ε approach, was put forward and validated. According to the simulated separation results of two cases, the root-mean-square error (RMSE) between predicted partition numbers of all density fractions and corresponding experimental values were 2.47 and 2.83 respectively, demonstrating the CFD model was able to give accurate simulation results. The Rosin-Rammler model was used to describe the size distribution characteristics (SDC) of the feed, with the parameter D_x and n describing the fineness and particles size variation of the feed respectively. Single-factor tests and central composite design were then developed and simulated using the CFD model to investigate the influence of the two aspects of SDC on the separation performance of LSFBS based on density. The simulated separation results indicate that the finer the feed is, the greater the separation density (δ_{50}) and E_p value are; the smaller the particles size variation is, the smaller the δ_{50} and E_p value are. According to the response surface analysis, the influence of feed fineness on δ_{50} is larger than that of particles size variation while the influence of feed fineness on E_p is smaller than that of particles size variation; the interactive effect between these two factors has a noteworthy influence on E_p but insignificant influence on δ_{50}.

1. Introduction

The volume of coal in the 0.25–3 mm size fraction that is processed in a mineral processing plant has increased significantly in recent years. This is somewhat due to the increased need to reprocess the middlings fraction in order to ensure a high coal recovery, with a good separation from the associated gangue. The beneficiation of this size fraction in the preparation plant is a relatively tough task, caused by the application of large diameter dense-medium cyclones and the limitation of the upper size of froth flotation (Korte and Bosnian, 2007; Li, 2008). Though dense-medium cyclones with a smaller diameter could achieve a more satisfactory separation efficiency for the fine coal, it is better practice to utilize a water-only separator for the fine coal beneficiation with less costs and ease of processing, such as a Liquid-solid Fluidized Bed Separator (LSFBS). However, the size distribution characteristics (SDC) of the feed particles could exert a notable influence on the separation performance based on the difference in particles densities, especially when a water-only separator is used. As a result, the coarse but light particles would be lost to the underflow (heavy products), and the small but dense particles would contaminate the overflow (light products) (Das et al., 2009; Epstein, 2005; Mukherjee and Kumar, 2009; Tripathy et al., 2015).

It is a very difficult and time-consuming job to obtain fine coal samples with particular SDC. Additionally, the proper mathematical model should also be determined to describe and control the SDC of the feed for a quantitative analysis on the influence of the two aspects of the SDC, i.e. the feed fineness and the particles size variation. This is most likely the reason why this problem remains unsolved by now.

Generally speaking, the amount of lost particles with different densities decreases with decreasing particle size variation. However, if the feed particles are finer than the lower limit of effective separation size range, the amount of lost particles will still be relatively large, even though the feed consists of mono-size particles (the particles size variation is the smallest). Although this effect has been well known and been established by various researchers (Galvin et al., 2005; Galvin et al., 2002; Sarkar and Das, 2010; Sun et al., 2016a), complete and systematic analyses are scarce; especially a quantitative analysis of the influence of the two aspects of the SDC.

In the present study, a new CFD model for Liquid-solid Fluidized Bed Separator (LSFBS), namely the Eulerian-Eulerian-Lagrangian/RNG k-ε approach, was put forward and validated. The separation results of the feed with various SDC in the LSFBS were obtained taking advantage of this CFD model with the Rosin-Rammler size distribution method

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used to control the SDC of the fine coal feed during the numerical simulation process. The principal objective of present study is to understand the influence of SDC of the feed on the separation performance of LSFBS in a quantitative way by using these simulated separation results.

2. Research method

2.1. Numerical simulation of particles separation in the LSFBSs

2.1.1. Geometry models and operating parameters of the LSFBSs

CFD methods are widely used to analyze various separators' flow fields and obtain predicted separation results (Cullivan et al., 2004; F and K, 2004; Mokni et al., 2015; Wang and Yu, 2006; Xia, 2007). There were three cases in this research: Case 1 (Lv and Zhu, 2012) and Case 2 (Sha et al., 2012)were used to validate the CFD model while Case 3 was used to predict the separation results of the feed of various SDC. The geometry models for the three cases were shown in Fig. 1, and the dimensions and operating parameters were listed in Table 1.

2.1.2. CFD model

The governing equations of mass and momentum for continuous phases are given as follows:

$$\frac{\partial u_i}{\partial x_i} = S_{C,P} \tag{1}$$

$$\rho\frac{\partial}{\partial t}(u_i) + \rho\frac{\partial}{\partial x_j}(u_i u_j) = -\frac{\partial p}{\partial x_i} + \rho\frac{\partial}{\partial x_j}\left(\nu\frac{\partial u_i}{\partial x_j} - \overline{u_i' u_j'}\right) + \rho g + S_{M,P} \tag{2}$$

where $S_{C,P}$ and $S_{M,P}$ are the mass and momentum source terms caused by the movement of particles, respectively.

The CFD model of LSFBS put forward in the present study is called the Eulerian-Eulerian-Lagrangian/RNG k-ε approach. The gas-liquid-solid three-phase system inside and outside the LSFBS was treated as the incompressible flow, and the RNG k-ε model was selected as the turbulence closure model, while the heat transfer during the separation was neglected. The interface between gas and liquid phase was predicted by an Eulerian-Eulerian approach using the Volume of Fluid (VOF) model; the movement of the discrete particles was calculated through Lagrangian method of discrete phase model (DPM). Although DEM (Discrete Element Method) can give more realistic movements of discrete particles, the Lagrangian method of DPM is computationally less expensive. The characteristics and suitability of these models for the gas-liquid-solid three-phase flow had been presented in detail by Sun et al. (2016b).

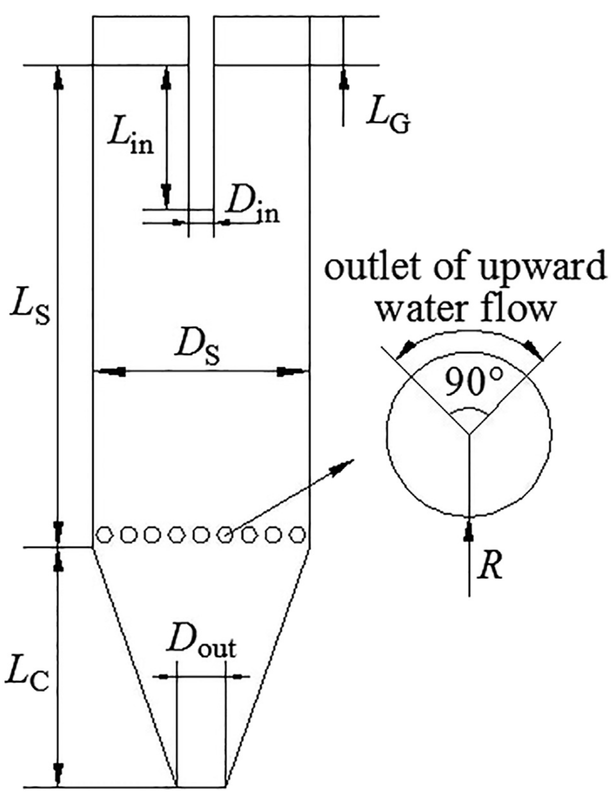

Fig. 1. Geometry model of LSFBSs.

Table 1
Dimensions and operating parameters.

Name	Symbol	Dimensions (mm)		
		Case 1	Case 2	Case 3
Diameter of cylinder	D_S	60	120	450
Length of cylinder	L_S	1700	1800	1000
Diameter of underflow	D_{Out}	25	35	100
Length of cone	L_C	10.5	21	500
Diameter of inlet pipe	D_{in}	6.7	15	50
Depth of inlet pipe	L_{in}	500	600	350
Height of air phase	L_G	100	100	100
Radius of upward water pipe	R	2.4	4.3	16
Upward water flow rate (m/s)	–	0.035	0.022	0.04
Feed rate (m/s)	–	0.04	0.04	0.1

The interaction between continuous phase and discrete phase was achieved using the two-way coupling method. The momentum exchange F during one continuous phase time step in the control volume can be calculated as

$$F = \sum\left\{\left[\frac{1}{\tau_P}(u_F - u_P) + f_x\right] m_P' \Delta t\right\} \tag{3}$$

where $(u_F - u_P) / \tau_P + f_x$ is the forces acting on per unit particle mass by the pressure and velocity fields of continuous phases in the time step; f_x stands for the forces excepting the drag force, including the virtual mass force, pressure gradient forces, velocity gradient forces (lift forces) etc. $\tau_P = [\rho_P d_P^2 / (18\,\mu)][24 / (C_D Re_p)]$ is the particle relaxation time and m_P' is the mass flow rate of the particles of the same diameter and density during the time step.

2.1.3. Discretization of the computational domains and governing equations

The computational domains of the LSFBSs in Case 1, 2 and 3 were discretized into the structured meshes shown in Fig. 2, consisting of 13,880, 14,352 and 16,424 control volumes, respectively. The control volumes around the distributor pipes and near to the separator's wall of Case 3 were refined to ensure the predicted flow fields near these zones were sufficiently accurate.

A no-slip wall boundary was specified with a standard wall function. The pressure staggered option (PRESTO) was used as the pressure interpolation scheme and semi implicit pressure-linked equations (SIMPLE) algorithm scheme was used for the calculation of the pressure and velocity fields. The modified HRIC discretization scheme was computationally inexpensive and could give a sharp resolution of the gas-liquid free surface. Hence, the modified HRIC was used for calculating the air volume fraction with the VOF multi-phase model. Finite volume method (FVM) was used for the discretization of the governing equations and all physical quantities at the grid node were calculated according to the values at the neighboring control volume surfaces through the quadratic upwind interpolation convective kinematics (QUICK) scheme. Time step size was determined as 0.005 s for the solution. When the residuals of the predicted velocities and volume fraction of the air phase