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Numerical simulation of the in-line pressure jig unit in coal preparation

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ABSTRACT

This paper presents a numerical study of the multiphase flow in an in-line pressure jig (IPJ), which is a high yield and high recovery gravity separation device widely used in ore processing but may have potential in coal preparation. The mathematical model is developed by use of the combined approach of computational fluid dynamics (CFD) for liquid flow and discrete element method (DEM) for particle flow. It is qualitatively verified by comparing the calculated and measured results under similar conditions. The effects of a few key variables, such as vibration frequency and amplitude, and the size and density of ragging particles, on the flow and separation performance of the IPJ are studied by conducting a series of simulations. The results are analyzed in terms of velocity field, porosity distribution and forces on particles. The findings would be helpful in the design, control and optimisation of an IPJ unit.
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1. Introduction

The use of jigging machinery for the classification and beneficiation of ore has a long history. Classic jigging units characteristically dilate the particle bed by an upward blast of water caused by the movement of a remote piston through a screen. Particles of different densities are then likely to segregate when they settle. Repeating such an operation makes the lighter particles remain on the top layer and the heavier particles drop down to the bottom layer. These particles can then be collected at either end to meet specific product requirements. These units were popular during and prior to the 1980s. In the 1990s, the jigging unit was improved by incorporating a centrifugal action in the unit (Beniuk et al., 1994). However, recent technological developments have resulted in jigging technology becoming an even more sophisticated tool of classification. For example, the invention of the 'in-line pressure jig' (IPJ) resulted in a more sophisticated classifier and can achieve even higher levels of efficiency. When using this method, a screen is moved up and down in a cyclic manner by means of a hydraulically powered servo that is mechanically linked to the screen. Moreover, the entire process occurring in a confined pressurized environment, adding a new dimension of security to the unit.

During the last decade, the IPJ has grown extensively in its technology in applications in the metalliferous industry. More recently, it is being considered as an alternative means to the dense medium cyclone for processing coal particles in large size ranges (0.25–30 mm). Some pilot scale tests have been performed to investigate the effects of the operational conditions for optimization of the control of IPJ in such separations (Vince et al., 2007). However, due to the complicated nature of the system and the number of the parameters involved, the full optimization through experimental studies is not an easy task. The lack of the fundamental understandings of such processes is the key motivation for a theoretical study.

There are few fundamental studies on the classification mechanism of the jigging devices in the current literature. Steiner (1996) studied the classical jigging device with only bare basics being debated. Galvin et al. (2002) and Mishra and Adhikari (1999) investigated the water flow in the jigging process in a simple geometry. Nesbitt et al. (2005) discussed only the effects of vibrating conditions on the jigging process in IPJ, although other parameters such as the properties of the ragging particles on the screen are also very critical.

In principle, the bulk behavior of particles in a system depends on the collective outcome of the interactions between individual particles, particles and boundary walls, and particles and fluid. Therefore, an investigation of the particle flow inside an IPJ on a particle scale should provide insight into the classification mechanism of the unit. Experimentally, such an investigation is challenging because the access to an IPJ is difficult being a confined pressurized unit. However, numerical simulation based on the so-called discrete element method (DEM) (Cundall and Strack, 1979) provides an effective away to perform such studies. This method has been applied in the study of particle–fluid flow processes in various industrial processes and is shown to be very

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useful in understanding the fundamentals (Zhu et al., 2007, 2008). In particular, it has been adapted for modeling the vibrating screening process (Dong et al., 2009).

In this work we present a three-dimensional CFD–DEM model, which is capable of simulating an IPJ unit. The model is validated by comparing the calculated and measured results under similar conditions. The effects of a few key variables on the flow and separation performance of the IPJ are studied by conducting a series of controlled numerical experiments, the key variables being the vibration conditions and properties of ragging particles. The numerical results are analyzed in terms of forces on particles, particle and fluid velocities and porosities of the particle bed, which present a better understanding on the particle–fluid flow in the IPJ unit.

2. Model description

Fig. 1a shows the working principle of the IPJ schematically. For confidential reasons, the detailed dimensions are not given here. The whole unit is sealed, hutch water and slurry (including water and coal particles) is pumped in. Ragging particles are put onto the screen. The upper part of the IPJ, including the upper part of the inner chamber with ring shape apertures on the wall, the screen and the feeding bowl, is continuously vibrated with jig-saw motions. Coal particles are fed from the top tube into the IPJ, and they either flow out through the apertures on the inner wall and then to the product outlet, or pass through the screen and discharged from the tails or reject outlet.

A coupled CFD–DEM model is developed here to model the system. In DEM, the particle flow is treated as a discrete phase, and the translational and rotational motions of particles are determined by Newton's law of motion, which can be written as

$$m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{f}_{p-f,i} + \sum_{j=1}^{k_i} (\mathbf{f}_{c,ij} + \mathbf{f}_{d,ij}) + m_i\mathbf{g} \quad (1)$$

and

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{k_i} \mathbf{T}_{ij} \quad (2)$$

where m_i, I_i, k_i, $\mathbf{v}_i$, and $\boldsymbol{\omega}_i$ are, respectively, the mass, momentum of rotational inertia, number of contacting particles, translational and rotational velocities of particle i; $\mathbf{f}_{f-p,i}$ and $m_i\mathbf{g}$ are the force between particle and fluid and gravitational force, respectively; and $\mathbf{f}_{c,ij}$ and $\mathbf{f}_{d,ij}$, and $\mathbf{T}_{i,j}$ are the contact force, viscous contact damping force and torque between particles i and j. These individual interaction forces and torques are summed over the k_i particles in interaction with particle i. The particle–particle or particle–wall contact force is calculated according to non-linear models commonly used in DEM, as recently reviewed by Zhu et al. (2007). The particle–fluid interactions include the buoyancy force and the drag force. The drag force is calculated according to Di Felice's correlation (1994). The equations used to calculate the forces and torques involved in Eqs. (1) and (2) can be found elsewhere (Dong et al., 2008; Kuang et al., 2008).

In CFD, the water flow is treated as a continuous phase and modeled in a way similar to the one in the conventional two-fluid modeling. Thus, its governing equations are the conservation of mass and momentum in terms of local mean variables over a computational cell, given by

$$\nabla \cdot (\rho_f \mathbf{u}) = 0 \quad (3)$$

and

$$\nabla \cdot (\rho_f \mathbf{uu}) = -\nabla P - \nabla \cdot \boldsymbol{\tau} + \rho_f \mathbf{g} - \mathbf{F}_{p-f} \quad (4)$$

where $\rho_{,}$ $\mathbf{u}$, P and $\mathbf{F}_{p-f}$ are, respectively, the fluid density, velocity, pressure, and the volumetric forces between particle and fluid; $\boldsymbol{\tau}$ is fluid viscous stress tensor, calculated according to standard k–e turbulent model.

DEM is solved by an object-oriented-programming based in-house code which can handle dynamic and complex boundaries and calculate the fluid–particle forces with the fluid flow field introduced from CFD simulation (Dong et al., 2008). The model has been successfully used in the simulation studies of complicated

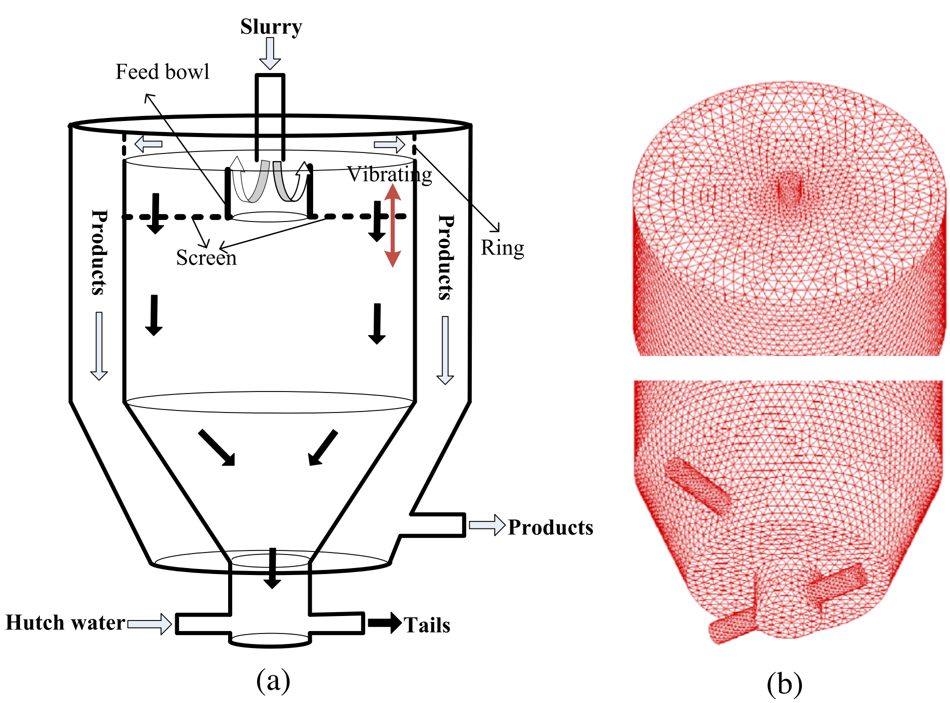

Fig. 1. (a) Schematic representation of in-line pressure jig and (b) the mesh used in CFD.

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