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Computational investigation of the mechanisms of the "breakaway" effect in a dense medium cyclone

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ABSTRACT

The motion of coal particles and the "breakaway" effect in an industrial dense medium cyclone of body diameter 1000 mm are studied by a computational fluid dynamics model. In the model, mixture multiphase model is employed to describe the flow of the dense medium (comprising finely ground magnetite contaminated with non-magnetic material in water) and the air core, where the turbulence is described by the well-established Reynolds Stress Model. The stochastic Lagrangian Particle Tracking method is used to simulate the flow of coal particles. It is shown that for coarse coal particles with size larger than 1 mm, the separation is mainly determined by the difference between the inward pressure gradient force and the outward centrifugal force, and the effect of drag force can be ignored. For finer particles with size less than 1 mm, however, the effect of stochastic drag force becomes significant. As a result, fine particles have an apparent fluctuating velocity and a relatively uniform distribution in the cyclone; and the drag force is so dominant that particles flow with fluid closely and the pressure gradient force is relatively so small to be able to effectively separate particles by density in the radial direction. This results in a significantly deteriorated separation efficiency of fine particles and the "breakaway" effect.

1. Introduction

Dense medium cyclones (DMCs) are the most important cleaning unit within coal preparation plants. Their working principle has been well documented (for example, see King and Juckes, 1984; Svarovsky, 1984; Wills, 1992). The feed, which is a mixture of dense medium slurry and raw coal, enters tangentially near the top of the cylindrical section under pressure, thus promoting a strong swirling flow. The refuse or high ash particles move towards the wall where the axial velocity vector points downward and are discharged through the spigot. The lighter clean coal moves towards the longitudinal axis of the cyclone, where there is usually an axial air core present and the axial velocity vector points upward and passes through the vortex finder. The invention of DMC about 70 years ago has been followed by continuous improvement. DMCs have proven to be effective in the coal industry. Today DMCs process the vast majority of tonnes fed to coal preparation plants.

The flow in a DMC is very complicated with the presence of swirling turbulence, air core and particle segregation, and involves multiple phases: gas, liquid, coal and magnetic/non-magnetic particles of different sizes and densities. Normally, the slurry including water, magnetite and non-magnetic content is termed "medium". Precise measurement of the velocity field in a DMC is very difficult, mainly because of the presence of magnetite particles in the medium. Therefore, the experimental study of the flow field in DMCs is mainly limited to the effects of geometrical and operational conditions on DMC performance (Fourie et al., 1980; Napiermunn and Scott, 1990; Restarick and Krnic, 1991; He and Laskowski, 1994; Klima and Kim, 1998; Svoboda et al., 1998; Ferrara et al., 2000; Dunglison and Napier-Munn, 2002; Turek and Klima, 2003). For the internal flow structure, the density distribution of medium in a DMC has been reported by Galvin and Smitham (1994) using X-ray tomography and by Subramanian (2002a) using gamma ray tomography (GRT).

In the past two decades, significant progress has been made in the mathematical modelling of DMC process based on computational fluid dynamics (CFD) (Holtham, 2006; Narasimha et al., 2006; Narasimha et al., 2007; Wang et al., 2009a). Wang et al. (2009b, 2011) studied the effects of body dimensions and medium properties on the separation performance in a 1000 mm DMC. Chu et al. (2009a) developed a CFD-DEM (discrete element method) model to reproduce some typical flow phenomena including "surging" in DMCs. The detailed flow field and particle flow pattern can be reproduced. It can offer a better way to study the mechanism of particle separation in a DMC. Moreover, the effects of the fluctua-

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tion of solids flow rate and vortex finder outlet pressure were also investigated by Chu et al. (2012a,c).

Previously, few papers reported the detailed mechanism of particle separation in a DMC. It was reported that the centrifugal forces cause the refuse or high ash particles to move towards the wall from where they were discharged through the underflow orifice or the spigot (Napier-Munn and Scott, 1990; Wood, 1990; Narasimha et al., 2006). He and Laskowski (1994) experimentally studied the effects of some medium properties on the separation performance. They found that the separation performance of fine particles was more sensitive to the change in medium rheology while the separation efficiency and cut point shift (or off-set) for coarse particles were mainly determined by the medium stability. Recently, Chu et al. (2009a) used a CFD-DEM model to study the separation mechanism in terms of the interaction of the fluid drag force, pressure gradient force, and various inter-particle forces, in addition to the gravity force. Additionally, the effect of particle density distribution that represents the major difference between two major coal types, i.e., coking coal and thermal coal, was studied (Chu et al., 2009b; Chu et al., 2012b). However, the mechanism of some special phenomena in DMCs is still not well understood, such as the breakaway effect. For a given cyclone diameter, there is a particle size, termed the "breakaway size", below which Ep (Ecarp Probable) deteriorates rapidly. The effect was found by many industrial investigators (Wood, 1990; Weale and Swanson, 2002; Sherritt et al., 2010), while the mechanism was not seriously studied.

This paper presents a numerical study of the particle flow and breakaway effect in a DMC. The dynamics of solid particles is analysed using the stochastic Lagrangian model. The results are found to be useful in understanding the mechanisms about the breakaway effect, which should be part of a comprehensive picture about how and why a DMC works.

2. Mathematical model

2.1. Model description

According to the previous work (Wang et al., 2009a), the modelling process was divided into three steps, as shown as Fig. 1. In Step 1, only air and slurry with a certain density were considered. The two phases were treated as fluids of homogeneous viscosity and density. Turbulent flow was modelled using the Reynolds Stress Model (RSM), and the Volume of Fluid (VOF) free surface model was used to describe the interface between the medium (defined as the mixture of water, magnetite and non-magnetic particles) and the air core (here defined as the regions with air volume fraction larger than 90%). In this step, the primary position of the air core and the initial velocity distributions were obtained. In Step 2, six additional phases were introduced to describe the behaviour of magnetite particles with different sizes. The multiphase model was changed from the VOF to the so-called mixture multiphase model. A correction is also necessary to estimate the viscosity effect of magnetite and non-magnetic particle size distribution. Detailed density and velocity distributions of different phases are obtained at the end of this step. In Step 3, the results of the fluid flow were used in the simulation of the flow of coal particles described by the stochastic Lagrangian Particle Tracking model (LPT). The characteristics of the DMC separating performance, such as partition curve and medium split, were then estimated.

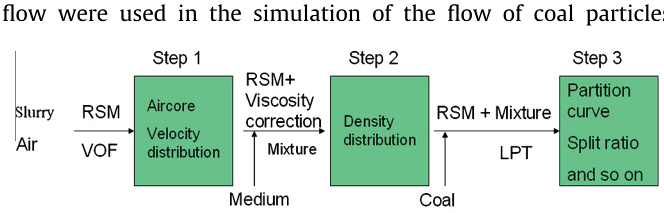

Fig. 1. Steps used in the present modelling.

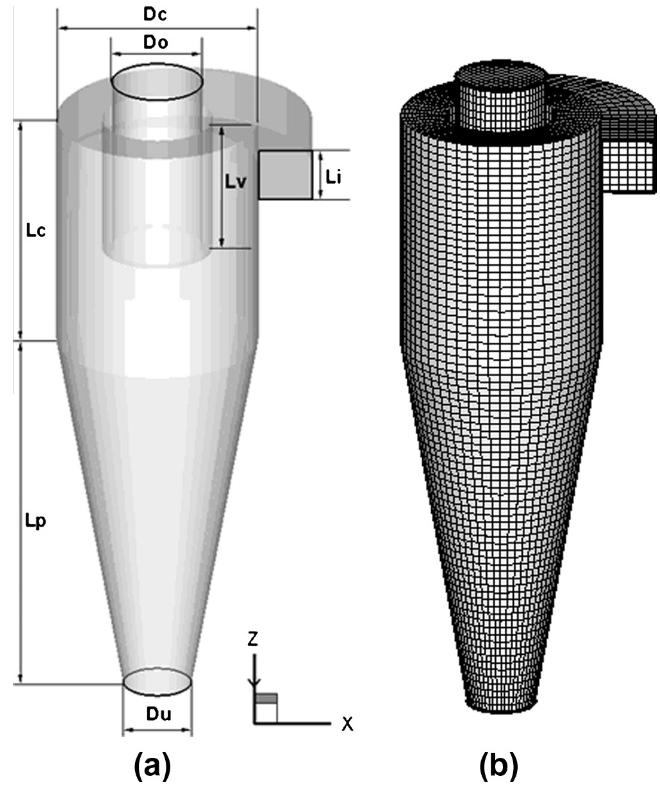

Fig. 2. Geometry (a) and mesh (b) representation of the simulated DMC (Dc = 1000 mm).

Therefore, the whole process involved four CFD models for different phases and one viscosity correction model. Details and justification of the use of these models can be found elsewhere (Wang et al., 2009a). Below the model to describe the flow of particles is briefly described because it is directly related to the discussion in this work.

The motion of a particle of mass m, density ρ_p and particle size d_p is described by the stochastic Lagrangian multiphase flow model. The liquid drag force and pressure gradient force on particles are calculated in the Lagrangian reference frame, given by

$$\frac{d\vec{u}_p}{dt} = E_D(\vec{u} - \vec{u}_p) - \frac{\nabla p}{\rho_p} + \vec{g} \quad (1)$$

where E_D is the drag coefficient, given by

$$E_D = \frac{18\mu}{d_p^2\rho_p} C_D \frac{\mathrm{Re}_p}{24} \quad (2)$$

where $\vec{u}_p$ is the particle velocity and $\vec{u}$ is the velocity of the fluid phase. Re_p is the relative Reynolds number, which is defined as $\mathrm{Re}_p = \frac{\rho d_p |u_p - u|}{\mu}$.

In the stochastic tracking, the turbulent dispersion of particles is predicted by integrating the trajectory equations for individual particles, using the instantaneous fluid velocity, $\bar{u} + u'$, along the particle path during the integration. The values of u' that prevail during the lifetime of the turbulent eddy are sampled by assuming that they obey a Gaussian probability distribution:

$$u' = \zeta\sqrt{\overline{u'^2}} \quad (3)$$

where ζ is a normally distributed random number. Since the kinetic energy k of turbulence is known at each point in the flow, the values