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Numerical investigation of the separation behaviours of fine particles in large dense medium cyclones

Z. Qi [a], S.B. Kuang [a,b,*], A.B. Yu [a,b]

[a] Laboratory for Simulation and Modelling of Particulate Systems, Department of Chemical Engineering, Monash University, Clayton, Victoria 3800, Australia
[b] Laboratory for Simulation and Modelling of Particulate Systems, School of Materials Science and Engineering, The University of New South Wales, Sydney, NSW 2052, Australia

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ABSTRACT

Use of large dense medium cyclones (DMCs) is a potential trend in the coal industry but its usage is limited by the poor separation efficiency of fine particles. This paper presents a numerical study of the multiphase flows and performance of DMCs used for coal preparation by means of the two-fluid model. The validity of the model has been verified by various applications. It is used here to study the behaviours of fine particles in a 2-m DMC that is larger than the biggest DMCs reported thus far in the coal industry. The numerical results show that in the extra-large DMC, the poor separation efficiency of fine particles gets worse compared to that of a widely used 1-m DMC. This deficiency is found to be attributed to the strong vortexes developed and the asymmetrical separation zone that can be characterised by the correlation between pressure gradient and tangential velocity. Several modifications with respect to mounting degree, operational Head, conical section length, and inlet number are introduced to improve the performance of the 2-m DMC. It is shown that the separation efficiency of fine particles in the 2-m DMC can be better compared to the 1-m DMC by increasing the Head or conical section length, because such modifications reduce the asymmetrical separation zone and/or amount of vortexes.

1. Introduction

Dense medium cyclones (DMCs) are a high-tonnage device for upgrading particles in the 50–0.5 mm size range. They have been proved to be effective in separating gangue from product coal according to density difference, and are used in processing the vast majority of tonnes fed to Australian coal preparation plants. Generally speaking, it has been the tendency in the coal industry to use larger DMCs to achieve higher capacities with the aim of mass-production, adapt to a wider range of particle sizes and simplify the operation process. However, DMCs generally suffer from poor separation of fine particles, leading to coal degradation to some extent, and this issue may be worsened significantly if the DMC size represented by body diameter is too large (Bosman and Engelbrecht, 1998; Chen et al., 2012). This deficiency is one of key factors that limit the DMC size used in practice (Glenn and Sherritt, 2013; Meyers et al., 2014; Meyers and Sherritt, 2010; Sanders, 2007). In fact, the largest DMC size reported thus far in the coal industry is 1.5-m (Glenn and Sherritt, 2013; Sanders, 2007). To date, the feasibility of a larger DMC than the existing ones is unknown. Also, design and operational aspects of such a cyclone are not clear. In order to clarify these issues, it is necessary to study the flow behaviours in an extra-large DMC, especially for fine particles.

The flow in a DMC is very complicated because of the presence of swirling turbulence, air core and segregation, and involves multiphases: gas, liquid, solids and medium particles of different sizes. Some efforts have been made to experimentally study the flow in this separator, but such an experimental method is technically difficult and expensive. These situations force designers/controllers to rely on empirical equations to improve DMC performance through adjusting a series of variables such as operational, geometrical and material conditions. In the past, many studies have been done in this respect (see, e.g., Barbee et al., 2005; Davis, 1987; Ferrara et al., 1999; Honaker et al., 2000; Napier-Munn, 1991; Restarick and Krnic, 1991; Sripriya et al., 2001; Wood, 1990; Zughbi et al., 1991). However, empirical approaches have different inherent limitations in them. For example, the empirical works are often focused on phenomenological descriptions that rarely touch upon the underlying physics. Thus, the resulting equations can only be used within the extremes of the experimental data from which the model parameters were determined. Additionally, different sets of experimental data lead to different equations even for the same basic parameters. Therefore, it is desirable, and certainly more reliable, to develop a mathematical description of the fundamentals which govern the multiphase flows and predict the performance of DMC under different production conditions.

* Corresponding author at: Laboratory for Simulation and Modelling of Particulate Systems, Department of Chemical Engineering, Monash University, Clayton, Victoria 3800, Australia.
E-mail address: shibo.kuang@monash.edu (S.B. Kuang).

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In recent years, in line with the development of computational technology, various efforts have been made to develop mathematical models based on flow fundamentals. For example, two-fluid models (TFM) facilitated by the so called mixture model were developed to study the medium flow in DMCs (Brennan, 2003; Narasimha et al., 2006; Wang et al., 2009a; Zughbi et al., 1991). Note that such models are simply referred to as "mixture model" in the literature. They solve only one set of conservative equations in regards with momentum and mass governing equations to all phases but with an algebraic slip velocity model applied to each of the phases. Thus, the mixture model is thought as a simplified form of the TFM model that employs a full set of governing equations to each phase involved. Chu et al. (2009a) developed the first CFD–DEM (Computational Fluid Dynamics–Discrete Element Model) method for DMCs by combing mixture model for the medium flow and DEM for the coal flow. Their model has been used to study effects of various variables related to the DMC operation, such as M:C (medium-to-coal) volume ratio (Chu et al., 2009a), particle density distribution (Chu et al., 2009b), fluctuation of feed solid flowrate (Chu et al., 2012a), outlet pressure at the overflow (Chu et al., 2012b), and wear of cyclone walls (Chu et al., 2014). The CFD–DEM approach is theoretically rational and favourable for elucidating the fundamentals underlying various phenomena in terms of particle-scale flow structures and forces (Zhou et al., 2010). However, the computational time required to simulate a given DMC operational condition is in the order of many weeks/months on a single central processing unit available in the market. Moreover, the CFD–DEM approach cannot directly be applied to fine particles whose number could be up to billions in an industrial-scale DMC. These issues are not present in the Lagrangian particle tracking (LPT) method, which however traces only one particle rather than all the particles. LPT can be thought of as a simplified DEM model and is limited to the operation at a large M:C ratio when applied to DMC. By combing LPT with mixture model, different investigators studied DMC performance with respect to geometrical and operational conditions (Narasimha et al., 2007; Wang et al., 2009a,b, 2011, 2014; Zughbi et al., 1991). Based on their CFD–LPT and CFD–DEM simulation results, Chen et al. (2012, 2014) developed a PC-based model to conveniently optimize design and operation of DMC under a wide range of conditions. More recently, Kuang et al. (2014) developed a TFM model to describe the flows of the medium and coal particles in DMCs at different M:C ratios based on the models respectively for the liquid–air–solid flow in hydrocyclones (Kuang et al., 2012; Wang and Yu, 2006) and the medium flow in DMCs (Wang et al., 2009a). Their results showed that the developed model can be successfully used to reproduce the behaviours of both coarse and fine particles with reasonable computational efforts. Clearly, various achievements have been obtained from the previous studies. However, to date, works dedicated to the studies on the behaviours of fine particles in DMCs have not been reported in the literature. Moreover, the DMC sizes considered in the studies so far have been, to a large extent, confined to the size range of the current DMC practice. However, the DMC practice is moving towards using larger DMCs in the future.

In this paper, the two-fluid model reported elsewhere (Kuang et al., 2014) is used to study the behaviours of fine particles in an extra-large (2-m) DMC, which is beyond the size range reported previously. The results are compared with those obtained from the widely used 1-m DMCs. By analysing the fluid dynamics of both DMCs, several modifications are introduced in relation to geometries and operational conditions, to improve the performance of the extra-large DMC.

2. Simulation method and conditions

2.1. Model description

The details of the model used have been reported elsewhere (Kuang et al., 2014). More information about the relevant theoretical and numerical treatments can also be found in other studies (Kuang et al., 2012; Wang et al., 2009a; Wang and Yu, 2006). For completeness, we describe here the key features of the model.

The mathematical model is a TFM model facilitated with the mixture model. In the model, both fluid (liquid and air) and solid phases (magnetite and coal particles) are treated as interpenetrating continua. Particles of different sizes or densities represent different phases. The flow of liquid–gas–solid mixture (as a single phase) is calculated from the continuity and the Navier–Stokes equations based on the local mean variables over a computational cell considering slip velocities between different phases (Manninen et al., 1996), which are given by:

$$\frac{\partial}{\partial t}(\rho_m) + \frac{\partial}{\partial x_i}(\rho_m u_m) = 0 \tag{1}$$

and

$$\frac{\partial}{\partial t}(\rho_m u_{mi}) + \frac{\partial}{\partial x_j}(\rho_m u_{mi} u_{mj}) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\sum_{k=3}^{n} p_k\right) + \frac{\partial}{\partial x_j}\left[\mu_m\left(\frac{\partial u_{mi}}{\partial x_j} + \frac{\partial u_{mj}}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho_m \overline{u'_{mi} u'_{mj}}\right) + \frac{\partial}{\partial x_j}\left(\sum_{k=1}^{n} \rho_k u_{dr,ki} u_{dr,kj}\right) + g\rho_m \tag{2}$$

where m represents the liquid–gas–solid mixture, n is the number of phases, g is the gravitational acceleration, ρ is the fluid density, u is the fluid velocity, μ is the fluid viscosity, g is the gravitational acceleration, t is the physical time, p_k is the solid pressure, $u_{dr,ki}$ is the drift velocity, and $-\rho_m \overline{u'_{mi} u'_{mj}}$ is the Reynolds stress term which includes turbulence closure and must be modelled to close Eq. (2).

To model anisotropic turbulence problems, turbulence models like the Reynolds stress model (RSM) or Large eddy simulation (LES) should be used, which can both give results comparable to the experimental measurements (Brennan, 2006; Mousavian and Najafi, 2009; Wang and Yu, 2006). For computational efficiency, the RSM model combined with a standard wall function is here adopted, similar to the CFD–DEM and CFD–LPT modelling of DMC (Chu et al., 2009a; Wang et al., 2009a):

$$\frac{\partial}{\partial t}\left(\rho_m \overline{u'_i u'_j}\right) + \frac{\partial}{\partial x_k}\left(\rho_m u_k \overline{u'_i u'_j}\right) = D_{T,ij} + P_{ij} + \phi_{ij} + \varepsilon_{ij} \tag{3}$$

where $D_{T,ij}$, P_{ij}, ϕ_{ij}, and ε_{ij} represent the turbulent diffusion, stress production, pressure strain, and dissipation, respectively.

In Eqs. (1)–(3), the mass-averaged velocity u_{mi}, and mixture density ρ_m of a mixture are respectively defined based on all phases involved:

$$u_{mi} = \frac{\sum_{k=1}^{n} \alpha_k \rho_k u_{ki}}{\rho_m} \tag{4}$$

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \tag{5}$$

where $k = 1$ corresponds to water, $k = 2$ to air, and $k = 3 - n$ to kth type of coal or magnetite particles. The water is treated as the primary phase and other phases as the secondary phases in this study.

The volume fraction of phase α_k is obtained according to the continuity equation for phase k:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \frac{\partial}{\partial x_i}(\alpha_k \rho_k u_{mi}) = -\frac{\partial}{\partial x_i}(\alpha_k \rho_k u_{dr,ki}) \tag{6}$$

where $u_{dr,ki}$ is the drift velocity for air or solid phase and described by the algebraic slip mixture model assuming that the phases should be reached over a short spatial length. Its calculation is based on the