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CFD-DEM STUDY OF THE MULTIPHASE FLOW IN A DENSE MEDIUM CYCLONE: PREDICTION OF WEAR

K.W. CHU[1*], S. B. KUANG[1], A.B. YU[1] and A. VINCE[2]

[1]Lab for Simulation and Modelling of Particulate Systems, School of Materials Science and Engineering, The University of New South Wales, Sydney, NSW 2052, Australia
[2]Elsa Consulting Group Pty Ltd, PO Box 8100, Mt Pleasant, QLD 4740, Australia
*Corresponding author, E-mail address: kaiwei.chu@unsw.edu.au

ABSTRACT

Dense medium cyclone (DMC) is a high-tonnage device that is widely used to upgrade the run-of-mine coal in coal preparation industry. It is known that wear is a serious problem in the operation of DMCs, but is not well understood. In this work, the wear rate of DMC walls due to coal particles is first predicted by combining computational fluid dynamics and discrete element method (referred below as CFD-DEM method), facilitated by a wear model from the literature. The numerical results show that the "groove" wear pattern observed in the practice can be predicted by the approach, and severe wear is also predicted to occur on the inside wall of the spigot and outside wall of the vortex finder. This work suggests that the developed CFD-DEM approach could be a useful tool to study the effect of wear in DMCs under different conditions.

KEYWORDS: Dense medium cyclone, multiphase flow, computational fluid dynamics, discrete element method, erosion, wear.

INTRODUCTION

DMC is a high-tonnage device that has been widely used to upgrade run-of-mine coal of 0.5-50 mm size range in the modern coal industry by separating gangue from product coal. The slurry fed to a DMC consists of multiple phases: air, water, coal and magnetic/nonmagnetic particles of different sizes, densities and other properties. Normally, the slurry (excluding coal particles) is named "medium" in practice.

The general working principle of DMC has been well documented in the literature (e.g., Wills, 1992). Fig.1 shows a schematic presentation of a DMC. The coal-medium mixture enters tangentially near the top of the cylindrical section, thus forming a strong swirling flow. Centrifugal forces cause the refuse to move towards the wall, where the axial velocity points predominantly downward, and to discharge through the spigot. The lighter clean coal particles, driven by pressure gradient force and radial fluid drag force, move towards the longitudinal axis of the DMC, where the predominant axial velocity points upward, and the coal exits through the vortex finder.

Despite being widely used, problems are frequently encountered in the operation of DMCs. Typical problems are the so-called "surging" phenomenon (which may happen frequently and can lead to a large portion of coal product misplaced to reject), vortex finder overloading, severe wearing of DMC walls, difficulties in scale-up, system instability, and even confusion regarding influencing factors.

The experimental work on DMC has been notoriously cumbersome and expensive, and seldom conducted. The mathematical descriptions of DMCs are sparse in the literature.One of the earliest numerical models was due to Zughbi et al. (1991). This was an oversimplified approach in which axis symmetry was assumed and the Prandtl mixing-length turbulence model adopted. Suasnabar and Fletcher (2003) reported a 2D model to predict the velocity distribution in a 200 mm diameter DMC. Brennan (2003) used a mixture multiphase flow model to simulate the medium segregation under the experimental conditions of Subramanian (2002). His model was further developed by Narasimha et al. (2007), which was used to describe the density distributions in a 350 mm DMC. On the other hand, in connection with the CFD model, the flow of coal particles can be modeled by use of the so-called Lagrangian Particle Tracking (LPT) method (Suasnabar and Fletcher, 2003 ; Narasimha et al., 2007 ; Wang et al., 2009). However, the LPT method is just suitable for dilute flow since it only traces a single particle, and the effect of inter-particle interactions and the reaction of particles on the fluid are ignored. Thus, the effect of coal flowrate, which is one of the most important operational parameters in DMCs, cannot be investigated using the LPT method. This can be overcome by the Combined Continuum and Discrete Model (CCDM or CFD-DEM) (Tsuji et al., 1992 ; Xu and Yu, 1997). In the CFD-DEM method, the motion of individual particles is obtained by solving Newton's equations of motion while the flow of continuum liquid is determined by CFD on a computational cell scale. DEM allows the direct consideration of particle-particle and particle-fluid interaction forces using Newton's laws, hence overcoming the problems associated with the continuum approach. The CFD-DEM model has been used to study DMCs in the literature (Chu et al., 2009a ; Chu et al., 2009b).

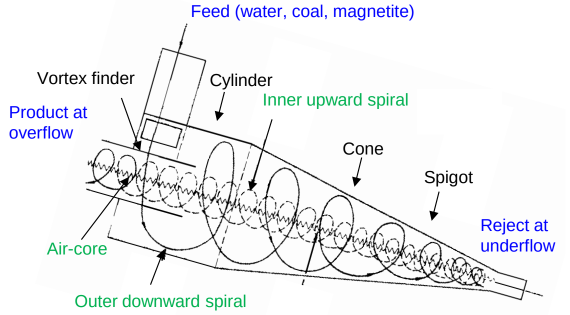


Figure 1. A schematic presentation of a DMC.

Excess wearing is a serious problem in the operation of DMCs, but it is not yet well understood. In practice, the lining of a DMC has to be replaced sometimes quite frequently due to wearing. It is important to predict the wear rate of the walls since the wearing of DMC walls would change the geometry of the DMC and thus affect its performance. Moreover, it is also important to locate the most severe wearing locations in a DMC and thus special treatment may be used correspondingly.

Wear on solid surfaces by particle abrasion is common in industrial processes and various machinery, some examples being sand blasting, pneumatic pipelines, and damage to helicopter propellers and turbine blades. In these cases, the target surface is attacked by solid particles entrained by a fluid stream. In general, the extent of the surface erosion by impingement of abrasive particles depends on the factors such as particle impinging velocity, impact angle, properties of the impacting particles and properties of target material (Fan et al., 1991). These concepts have been the foundation for most of the wear models including Finnie's wear model (Finnie, 1960) which has been widely used in many industrial processes (Chen et al., 1998 ; Bhasker, 2010 ; Lester et al., 2010). By far the majority of erosion models have been developed based on Finnie model or modifications to it. For DMCs, the only work found in the literature is done by Zughbi et al. (1991) who used a 2D CFD model to predict the wear rate in a DMC for use in diamond mines.

In this work, the prediction of the wear rate of the DMC walls is tried using a CFD-DEM method facilitated by the Finnei wear model (1960).

MODEL DESCRIPTION

In the CFD-DEM model, the motion of particles is modelled as a discrete phase, by applying Newton's laws of motion to individual particles, while the flow of fluid is treated as a continuous phase, described by the local averaged Navier-Stokes equations on a computational cell scale. The approach has been recognised as an effective method to study the fundamentals of particle-fluid flow by various investigators (Yu and Xu, 2003 ; Zhu et al., 2007) and its mathematical formulation has been well documented (Tsuji et al., 1992 ; Xu and Yu, 1997). Chu and Yu (2008) extended this model to study complex particle-fluid flow. However, only a single fluid phase is present in those studies. In this work, the continuous phase represents a mixture of water, air, and magnetite particles of different sizes and densities.

The continuous medium flow is calculated from the continuity and the Navier-Stokes equations based on the local mean variables over a computational cell, which are given by

$$\frac{\partial(\rho_f \varepsilon)}{\partial t} + \nabla \cdot (\rho_f \varepsilon \mathbf{u}) = 0 \qquad (1)$$

and

$$\frac{\partial(\rho_f \varepsilon \mathbf{u})}{\partial t} + \nabla \cdot (\rho_f \varepsilon \mathbf{uu}) = -\nabla P - \mathbf{F}_{p-f} + \nabla \cdot (\varepsilon \boldsymbol{\tau}) + \rho_f \varepsilon \mathbf{g} \qquad (2)$$

where ε, $\boldsymbol{u}$, t, ρ_f, P, $\mathbf{F}_{f-p}$, $\boldsymbol{\tau}$, and $\boldsymbol{g}$ are, respectively, porosity (equal to volume fraction of fluid), fluid velocity and time, fluid density and pressure, volumetric fluid-particle interaction force, fluid viscous stress tensor, and acceleration due to gravity. $\mathbf{F}_{f-p} = \sum_{i=1}^{k_c} \mathbf{f}_{p-f,i}$, where $\mathbf{f}_{p-f,i}$ is the total fluid force on particle i and k_c is the number of particles in a CFD cell. The flow solved in Eqs. (1) and (2) represents the mixture flow of medium and air, and was obtained by use of the Volume of Fluid (VOF) and Mixture Multiphase Flow (MMF) models in a commercial CFD software package, i.e. Fluent (see Steps 1 and 2 in Figure 2.). The details of the medium flow calculation and its validation can be found elsewhere (Wang et al., 2007 ; Chu et al., 2009a).

On the basis of the fluid flow obtained above, as the third step of the whole modelling approach shown in Figure 2. , the flow of coal particle can be modelled either by the LPT or DEM (Cundall and Strack, 1979). LPT model can be treated as an extreme case of DEM when only one particle is tracked in the DMC and the impact of solid/solid and solid/fluid interactions are ignored. According to DEM, a particle in a DMC was considered to have two types of motion: translational and rotational. During its movement, the particle may collide with its neighbouring particles or with the wall and also interact with the surrounding fluid, through which momentum and energy are exchanged. At any time t, the equations governing the translational and rotational motions of particle i in this two-phase flow system are:

$$m_i \frac{d\mathbf{v}_i}{dt} = \mathbf{f}_{p-f,i} + m_i \mathbf{g} + \sum_{j=1}^{k_i} \left(\mathbf{f}_{c,ij} + \mathbf{f}_{d,ij}\right) \qquad (3)$$

and

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{k_i} \left(\mathbf{T}_{c,ij} + \mathbf{T}_{r,ij}\right) \qquad (4)$$

where m_i, I_i, $\mathbf{v}_i$, and $\boldsymbol{\omega}_i$ are, respectively, the mass, moment of inertia, translational and rotational velocities of particle i. The forces involved are the gravitational force, $m_i\mathbf{g}$, inter-particle forces between particles i and j which include the contact forces $\mathbf{f}_{c,ij}$, and viscous damping forces $\mathbf{f}_{d,ij}$, and the total particle-fluid interaction forces, $\mathbf{f}_{p-f,i}$, which is the sum of various particle-fluid forces, including viscous drag force and pressure gradient force in the current case. Torques, $\mathbf{T}_{c,ij}$, are generated by the tangential forces and cause particle i to rotate, because the inter-particle forces act at the contact point between particles i and j and not at the particle centre. $\mathbf{T}_{r,ij}$ are the rolling friction torques that oppose rotation of the ith particle. Trial simulations indicated that other particle-fluid forces, such as virtual mass force and lift force, could be ignored in this work. The fluid properties used to calculate the particle-fluid interaction forces are those relating to the individual phases in the mixture, i.e., water, air and magnetite particles of different sizes. The details of the calculation of the forces in Eqs.(1)-(4) can be found in our previous studies (Zhou et al., 1999 ; Xu et al., 2000).

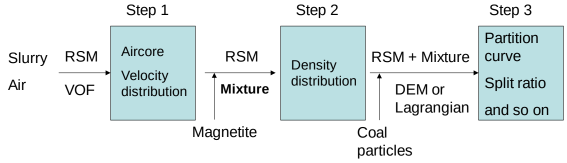


Figure 2. Schematic diagram of the modelling approach.

This step-wise approach offers a way to use the existing data for verifying the proposed model. In Step 1, the simulated results of water-air flow are compared against experimental data (Wang et al., 2007). In Step 2, the simulated medium density distribution is confirmed to agree well with experimental result by γ-ray tomography (Wang et al., 2009). In step 3, both DEM and Lagrangian particle tracking (LPT) models were added to the model to simulate the flow of coal on the basis of the developed CFD model. The simulated partition performance of coal particles of different sizes has been confirmed to compare favourably with the experiments (Chu et al., 2009b).

Wear model used in the present work is represented by the Finnei wear model (1960) which involves the use of concepts such as the kinetic energy and the angle of impact. Finnie's model has been developed based on a single rigid abrasive particle which strikes on the target surface so as to displace or cut away a part of the surface. Removal of material here is somewhat similar to the tooth of a milling cutter or the grains on a grinding wheel. The volume of material Q, removed by a single abrasive grain of mass, m, and velocity, v is given by:

$$Q = \begin{cases} \frac{mv^2}{8p}[\sin 2\alpha - 3\sin^2\alpha] & \alpha \le 18.5^o \\ \frac{mv^2}{24p}\cos^2\alpha & \alpha \ge 18.5^o \end{cases}$$

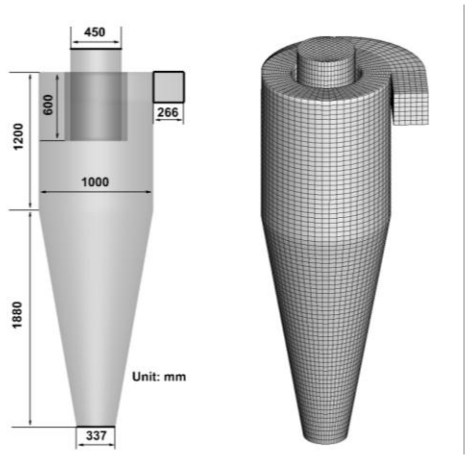
where p is the yield stress of the target material. Here, we assume that the wall lining is made of white cast iron which has the yield stress of 720 MPa.

SIMULATION CONDITIONS

The DMC considered in this work is, for convenience, similar to that used in the previous experimental (Rong, 2007) and numerical (Chu et al., 2009b) studies. The geometric parameters and mesh representation of the DMC are shown in **Figure 3**. The DMC has a square and involute inlet. It is divided into 80,318 hexahedral cells for the CFD computation. Three grid sizes were examined in our trial simulations, respectively giving 62,609, 80,318, 11,256 cells. The difference is less than 5% for all the results considered, suggesting that the present computed results are reliable, independent of mesh size. In line with practice, the DMC considered is operated at an orientation angle of 10 º(the orientation angle is defined as the angle between the DMC axis and horizontal axis). The operational parameters used in the simulations are summarised in Table 1.

Table 1. Operational parameters used in the simulations.

Phase	Parameter	Symbol	Units	Value
Solid	Density	ρ	Kg/m³	1200 to 2200 (even distribution)
	Particle diameter	d_i	mm	25
	Rolling friction coefficient	μ_r	mm	0.005
	Sliding friction coefficient	μ_s	--	0.3
	Poisson's ratio	ν	--	0.3
	Young's modulus	E	N/m²	1×10^7
	Damping coefficient	c	--	0.3
	Particle velocity at inlet	--	m/s	3.8
Gas	Density	ρ	kg/m³	1.225
	Viscosity	μ	kg/m/s	1.8×10^{-5}
	Velocity at inlet	--	m/s	3.9
Water	Density	ρ	kg/m³	998.2
	Viscosity	μ	kg/m/s	0.001
	Velocity at inlet	--	m/s	3.9
Magnetite	Density	ρ	kg/m³	4945
	Sizes (volume fractions in slurry)	--	µm	10 (4.0%), 20 (3.4%), 30 (1.9%), 40 (1.5%), 50 (1.3%) and 80 (1.1%)
	Viscosity	μ	kg/m/s	Ishii and Mishima (1984)
	Velocity at inlet	--	m/s	3.9
Medium	Density	ρ	kg/m³	1,550



(a) (b)

Figure 3. Geometry (b) and mesh (c) representation of the simulated large DMC (Dc=1000mm).

RESULTS

From the DEM simulation, complete information such as particle-wall impact velocity, impact angle, and their location can be obtained. When a particle is in contact with the wall, contact information is accumulated for each part of the wall. A square sampling surface area is used as the structure on which this data are collected and averaged.

In practice, it takes months before the wall lining needed to be replaced due to the wear. It is impossible for CFD-DEM models to simulate the whole wear process over such a long time. Instead, the present study adopted the following procedure to model the wear process. The simulation is firstly performed on a new wall for 30 second and the collisions and contacts between the particles and the wall are recorded and mapped onto a high resolution mesh that covers the walls. The wear of the walls due to the collisions is accumulated in sampling areas over the time so the amount of material worn out can be recorded. For a dynamically steady flow state (defined here as the state at which the flow character does not change much with time), it is assumed that the wear rate is constant with time or the amount of wear will increase with the time linearly. This enables us to calculate the wear rate for a month or year based on the wear rate in 30 seconds.

In our previous works, the possible wear problem is shown by use of the so-called Time Averaged Collision Intensity (TACI) (Chu and Yu, 2008), which is defined by

$$\mathrm{TACI} = \frac{\sum_{t=0}^{t=T}\sum_{i=1}^{k_m}\left|\mathbf{f}_{cn,i}+\mathbf{f}_{dn,i}+\mathbf{f}_{ct,i}+\mathbf{f}_{dt,i}\right|}{S_s \times T_s}$$

Where S_s is the area of a sample wall surface, T_s is the sampling time, k_m is the number of particles contacting with each other at a given time. $\mathbf{f}_{cn,i}$, $\mathbf{f}_{dn,i}$, $\mathbf{f}_{ct,i}$, $\mathbf{f}_{dt,i}$ and are particle-wall normal contact, normal damping, tangential contact and tangential damping interaction forces respectively. In the calculation, this is done by dividing the DMC, i.e. the computational domain, into many small elements and TACI is calculated for each element. Physically, it can be understood as the particle-wall interaction forces per unit volume per unit area.

It would be interesting to know the relationship between wear pattern and the TACI of particle-wall interaction. Figure 4 compares the simulated wear pattern and TACI of particle-wall interaction. It can be seen that their spatial distributions look very similar to each other. Both TACI and wear rate are high at the vortex finder, the top of the cylinder wall and the spigot wall. This proves that the TACI of particle-wall interaction can be used to qualitatively handle the wear problem.

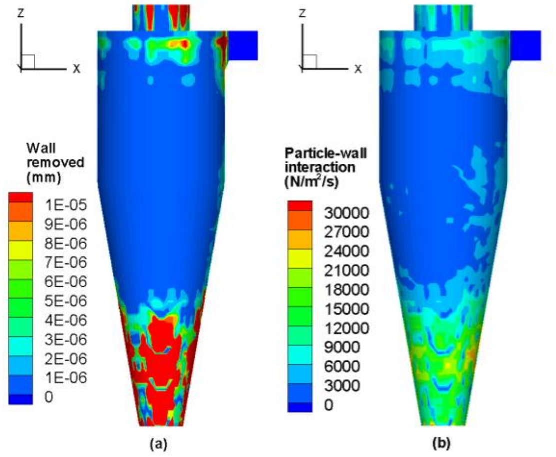


Figure 4. Simulated quantity of the wall removal within 30 seconds (a), and time-average particle-wall interaction intensity (b).

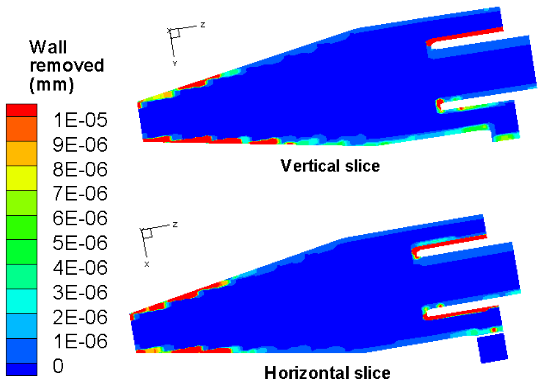


Figure 5. Simulated quantity of the wall removal and severe wear locations inside the DMC.

Figure 5 shows in detail the severe wear locations and wear rate inside the DMC considered. It can be clearly seen that the severe wear locations appear on the inside wall of the spigot or the lower part of the cone wall and the outside wall of the vortex finder. It can also be seen that the wear rate in the horizontal slice is largely symmetric. However, the wear rate in the vertical slice is non-symmetric and the wear rate at the bottom is generally higher than that at the top, which should be caused by the gravity forces that point from the top to bottom. It should be noted that this work only considers the wearing due to coal particles; the wearing due to medium flow is not considered.

CONCLUSION

A CFD-DEM model has been developed and used to predict the wear locations and rate in a DMC. The “groove” wear pattern observed in practice can be predicted by the approach. It is predicted that the severe wear locations are the inside wall of the spigot and the outside wall of the vortex finder.This work suggests that the developed CFD-DEM approach could be a useful tool to study the wearing in DMCs under different conditions.

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