13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

CFD SIMULATION OF DENSE MEDIUM CYCLONES

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ABSTRACT

Computational simulation of dense medium cyclones is being carried out. In this paper, a simplified Eulerian-Lagrangian model is proposed. This model considers homogeneous Newtonian fluid for the medium and coal particles are tracked in a Lagrangian reference frame. A Reynolds stress turbulence model is used to simulate turbulence inside of the cyclone. Predicted partition curve closely agree with experimental partition curves. Additionally, the air core is modelled using a VOF method. A modified version of the standard $k - \epsilon$ turbulence model was successfully used with this technique. The predicted air core shape and size agree well with experimental measurement. Finally, the segregation of the dense medium was also considered by using an Eulerian granular model. Results show that magnetite particles are segregated mainly in axial and radial directions.

INTRODUCTION

Dense medium cyclones (DMCs) are widely used coal-cleaning devices in the mining industry. For hard-to-clean (+10% near gravity material) in the size range of 50 mm to 0.5 mm, DMCs are very effective. In operation, the raw coal and the medium are fed at a precise pressure into the tangential inlet. The ensuing flow spirals towards the apex of the device. In the core of the cyclone, a very fast upward flow is created. Centrifugal classification causes shale to move outwards towards the inner wall of the conical shell. As a result, shale is discharged from the apex and coal is carried by the rising internal spiralling towards the vortex finder to be discharged from the overflow.

Empirical investigation and computational modelling of the flow pattern, pressure drop, solids motion and concentration profiles in hydrocyclones have been carried out by many researchers (Kesall,1952; Hsieh, 1988; Davison, 1994 and Devallapalli and Rajamani, 1996). However, for DMCs such information is very limited. DMCs have been mainly subjeted to experimental studies by several researches (Davis,1985; Napier-Munn,1990; Wood,1990) Therefore, the need for comparable investigation of DMCs is evident.

The present research is being carried with the aim of increasing the performance of dense medium cyclones. This research uses computational fluid dynamics. The first aim is to establish a reliable model for cyclones, then a systematic geometry modification will be carried out. This approach involves both single phase and multiphase predictions. Detailed modelling of DMCs involves prediction of the medium velocities, the magnetite and coal concentrations profiles, the turbulent viscosities, and the coal particles separation efficiency.

Physical Phenomena

There are several phenomena interacting with each other inside a DMC. The description of them and their implications for the modelling work are described in more detail by Suasnabar et al. (1998). Here, it can be summarized that the air core, the highly swirling flow with high curvature, the non-Newtonian behaviour of the magnetite medium and the segregation phenomenon of the medium (Napier-Munn, 1990) are the most important factors to be considered in the modelling. The air core can be either modelled or approximated by appropriate boundary conditions. For swirling flow with high curvature, a turbulence model which accounts for the interaction of the individual Reynolds stresses is recommended. Finally, the non-Newtonian rheology of the medium and the segregation phenomenon will require a multiphase granular model.

A SIMPLIFIED MODEL FOR DENSE MEDIUM CYCLONES

A model for DMCs requires first a model for the medium and then a model for the coal particles. A magnetite medium of $1500 kg/m^3$ made of ultrafine magnetite dispersed in water can be considered to be an homogeneous suspension (He, 1994). On the other hand, experimental measurements of stress-strain rate for this medium reported by Laskowski (1994) showed that the Newtonian assumption for this particular case can be a good approximation. Coal particles can be modelled in a Lagrangian frame, considering all forces acting on these particles. Additionally, particle-particle interaction and two ways particle-fluid interaction can be neglected under the assumption of dilute concentration. In fact, following the tracer technique described by Davis et al. (1985), coal particles can be added into the cyclone to determine performance curves for cyclones.

Turbulence Modelling

By far, the two-equation $k-\epsilon$ model is the most widely used in engineering due to its relative simplicity, robustness, economy and reasonable accuracy for a wide range of turbulent flows. However, it has long been recognized that this eddy viscosity model is not appropriate for highly swirling and strong curvature flows. In order to keep a simple turbulence model, several other models still based on the Boussinesq eddy-viscosity approximation have been proposed for this type of flow (Kobayashi and Yoda, 1987). The preferred method has been to consider additional higher order terms (Chen et al., 1997). On the other hand, second-order closure models accounts for the anisotropy of the eddy viscosity. These models are recommended for complex flows such as in cyclones. In the present research a Reynolds Stress Model described by Launder et al. (1975) has been used for the single phase flow. In this model, the diffusive transport and the pressure strain terms are approximated. Additionally, a parametrically modified version of the standard $k-\epsilon$ model presented by Suasnabar et al. (1998) was used, mainly for the multiphase models described below. The standard $k-\epsilon$ turbulence model described by Rodi (1980) was used as a base model. The modified parameter values are $C_{2\epsilon}=1.36$, $C_{\mu}=0.105$ and $\sigma_{\epsilon}=1.7$.

Air Core Modelling

Modelling of the magnetite medium under the assumptions of a Newtonian homogeneous fluid can be carried out with two approaches. The first one is to establish a two-phase model for the medium and air. Here, the medium and the air must be considered to be interacting with each other to create an air core along the axis of the cyclone and the medium flowing out of this region. The second approach is to consider a cylindrical air core with frictionless boundaries. The first approach is discussed in this section.

The air core is known to be fluctuating over time. Experimental observation and measurement presented by Wood (1990) has shown that the air core away from the vortex finder region is basically cylindrical in shape. The reported diameter size was about $30mm$. In this research, a 200 mm standard DMC was used. A 3D hexahedral O-type grid representing the cyclone was built. Then, the VOF model of Hirt and Nichols (1981) has been applied to model the air core. In this technique, tracking of the interphase between the medium and the air is accomplished by solving a continuity equation for the volume fraction α_f described below:

$$\frac{\partial \alpha_f}{\partial t}+u_j\frac{\partial \alpha_f}{\partial x_i}=0 \quad (1)$$

A single momentum equation is solved throughout the domain, and the resulting velocity field is shared by the two phases. During the solution of the transport equations, the volume-fraction average density and viscosity are used. Additionally the modified $k-\epsilon$ turbulence model is used to model turbulence. The result in terms of magnetite volume fraction depicted in Figure 1 shows that the shape of the air core is nearly cylindrical. However, a slightly smaller diameter of the air core is shown in the region just away from the vortex finder region. This is caused by the short-circuiting flow entering the vortex finder region.

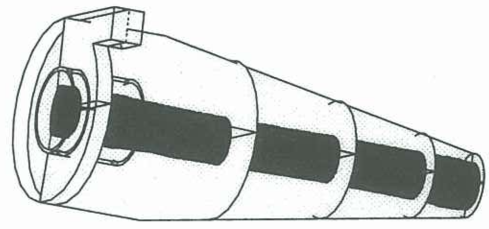

Figure 1: 3D Modelled Air Core of the Dense Medium Cyclone.

Simplified Treatment of the Air Core

As described in the previous section, steady-state calculations demonstrate that the air core is nearly cylindrical in shape and located axially-central. Therefore, in practice, any fluctuation in shape and location of the air core must be caused by the fluctuating feed conditions. For regular operating conditions, feed conditions are aimed to be kept constant. So under these conditions the air core can be considered cylindrical in shape. Then the air core-medium interphase is a free surface. Here the interphase is approximated as a sliding wall. In other words, a zero-gradient/zero-flux type of boundary conditions is imposed at the interphase.

A 3D hexahedral O-type grid was built for a domain restricted to the region outside of the air core. The governing equations in their time-averaged form were solved together with the Reynolds stress turbulence model described before.

The predicted result depicted in Figure 2 shows the existence of recirculation zones in the outer region of the vortex finder. The model also predicts that circunferenxial symmetry of the flow is reached down the vortex finder. Additionally, flow in the outer region is downward and in the core is upward. Also this figure shows clearly the short-circuiting flow on the outer wall of the vortex finder.

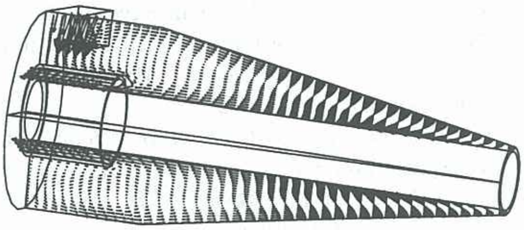

Figure 2: Axial and Tangential Velocity Vectors.

Particle Tracking in a Lagrangian Reference Frame

The Lagrangian method has been used to track coal particles of dilute concentration. The trajectory of the individual particle is predicted by integrating the force balance on the particle. For the x-direction in Cartesian coordinates, the equation written in a Lagrangian reference frame, is:

$$\frac{du_p}{dt} = \frac{18\mu C_D Re}{24\rho_p D_p^2}(u - u_p) + g_x\frac{\rho_p - \rho}{\rho_p} + \frac{1}{2}\frac{\rho}{\rho_p}\frac{d}{dt}(u - u_p) + \frac{\rho}{\rho_p}u_p\frac{\partial u}{\partial x} \qquad (2)$$

where the forces on the right-hand side represent respectively the drag force, the gravity force, the virtual mass force, and pressure gradient force. To predict the dispersion of the particle due to turbulence, the fluctuating medium velocity components were obtained by solving the Langevin equation described by Thomson (1987).

In Figure 3, the predicted partition curve performance is compared with curves obtained by experimentation. The result evaluated in terms of the partition number for coal particles at different densities, shows that the prediction is close to the float-sink experimental data.

MODELLING OF SEGREGATION OF THE MAGNETITE MEDIUM

The magnetite medium can be modeled with different basic assumptions. First, it can be considered as a homogeneous Newtonian fluid (previous section). Predictions with this assumption are combined with the Lagrangian approach to track particles (Figures 2,3). The alternative assumption is to consider magnetite and water as separated phases.

Strictly speaking, every different particle size of magnetite is a phase. Therefore, the actual representation of the medium will require a large number of phases. In practice, this is not possible due to computational limitations. Therefore, a representative particle size of the medium may be considered. In this research, a two-phase model was considered. Water was considered as the continuons phase in which magnetite particles of 20μ are dispersed. The study was carried out for a medium with specific gravity of $1500kg/m^3$. It is important to point out that in this case superfine magnetite instead of ultrafine of the previous model was considered.

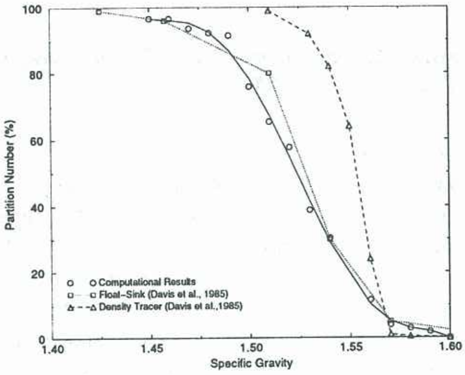

Figure 3: Predicted and Experimental Partition Curves.

In the Eulerian granular approach, the two phases are treated mathematically as interpenetrating continua. Momentum and continuity equations are solved for each phase and volume fractions are tracked. The model uses a single pressure field for the two phases. The momentum exchange between the two phases is based on the value of the fluid-solid exchange coefficient and the solid-solid exchange coefficient. The model uses a microstructural model (kinetic theory) in which macroscopic behaviour is inferred from the interaction between the particles. Therefore, non-Newtonian behaviour of the medium may be intrinsically captured. The generalised mathematical equations for this model are described in detail by Gidaspow (1994).

Figure 4 depicts the results in terms of magnetite concentration contours. It is shown that in fact the medium of superfine magnetite suffers segregation mainly in the axial and radial directions. Specific gravity as high as $1900kg/m^3$ occurs in the outer region near the apex. Whereas a specific gravity of nearly $1100kg/m^3$ is predicted in the inner region close to the vortex finder. The implications of the segregation phenomena in the simplified model may be neglected considering that the previous model was built for a medium with ultrafine magnetite. Additionally, in practice higher viscosities of the medium is expected due to contamination of the medium by clay and other fine contamination (Napier-Munn, 1990).

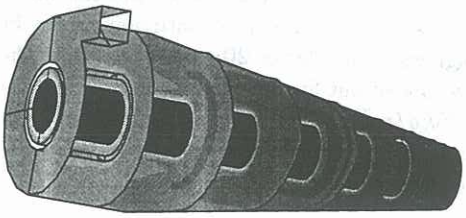

Figure 4: Segregation of 20μ Magnetite Particles in the Medium.

CONCLUSION

A simplified Eulerian-Lagrangian model for dense medium cyclones is presented. The magnetite medium with ultrafine particles is considered as an homogeneous Newtonian fluid and modeled in an Eulerian frame. Coal particles are modelled in a Lagrangian frame. As validation, the prediction of the partition curve is close to the one obtained by float-sink analysis.

Additionally, the air core is found to be cylindrical in shape with an average diameter of approximately 30 mm. Experimental measurement carried out by Wood (1990) validate this prediction.

Finally, it was found that segregation of the superfine magnetite particles in the water medium occurs basically in the axial and radial directions.

Future work will be oriented to formulate a more comprehensive model for DMCs including a cloud model for turbulent dispersion of the particles.

ACKNOLEDGEMENT

This project is financially supported by the Australian Postgraduate Award in Industry APA(I) and MIM, which are gratefully acknowledged.

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