MULTIPHASE CFD SIMULATIONS OF DENSE MEDIUM AND CLASSIFYING HYDROCYCLONES

Dr M. S. BRENNAN

The Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Isles Rd, Indooroopilly, Queensland, 4068, AUSTRALIA

ABSTRACT

Cyclones are widely used in the mineral processing industry to classify and concentrate mineral particle slurries. CFD simulations of dense medium and classifying cyclones have been conducted using FLUENT. The simulations use a three dimensional grid and the Reynolds Stress Turbulence Model. Classification and medium segregation and the air core are being modelled with the Algebraic Slip Mixture Model. The results are compared with density profiles from gamma ray tomography and plant classification data.

NOMENCLATURE

A_k particle cross-sectional area of phase k, m^2
C_d drag coefficient
$\boldsymbol{g}$ gravity vector – n
$\mathbf{M_p}'$ fluctuating component of interphase momentum transfer
$\mathbf{u_{kc}}$ velocity vector of phase k relative to continuous phase, m.s^{-1}
$\mathbf{u_{km}}$ velocity vector of phase k relative to mixture velocity, m.s^{-1}
$\mathbf{u_m}$ mixture velocity vector, m.s^{-1}
V_k particle volume of phase k, m^3

α_k volume fraction of dispersed phase k
ρ density, kg.m^{-3}.
τ_t turbulent stress tensor

INTRODUCTION

Cyclone separators are used extensively in the chemical and mineral processing industries to remove or classify particles in particle laden fluid flows. The devices rely on the centrifugal forces that develop under the swirling flow inside the body to effect the separation and can classify on density or particle size. They are essentially a passive device with a short residence time, which makes them easy to run. However the fact that they treat particle-laden flows means that wear and its minimization is a major problem.

Dense medium cyclones (DMCs) are used in the mineral processing and coal industries and operate with a finely divided dense particulate phase (the medium) as part of the feed. This solid phase has the effect of increasing the overall fluid density and permits a separation between mineral and gangue or coal and waste particles based on differences in particle density. In operation, the medium segregates with higher concentrations of medium reporting to the underflow. Further, whilst the mineral is the usually the more dense material in the slurry and should report to the underflow, it is often the finer material in terms of size and this reduces the separation efficiency.

Classifying cyclones are used to effect a separation based largely on particle size and here a major concern is to design cyclones so that the cut point on size is as sharp as possible.

Modelling the hydrodynamics of cyclones by CFD is a key to understanding these effects, however this is a non-trivial computational challenge. The flow is turbulent. Further cyclone separators rely on developing a strong swirl with a flow reversal near the underflow to effect classification. This makes the flow strained and introduces anisotropy into the turbulence. Most cyclones which process particle laden liquids develop an air core because the swirling flow generates a region of negative gauge pressure along the axis. Finally the devices treat particle-laden flows. In gas cyclones the CFD solution becomes a 2-phase problem and is a 3-phase flow problem in liquid cyclones if the CFD is used to model the position of the air-core.

The CFD problem is made worse because the detailed experimental information needed to validate the models is difficult to obtain. The presence of particulate minerals renders cyclone feed slurries opaque and Laser Doppler Anemometry cannot be used unless an experimental slurry of glass beads with a fluid of the same refractive index is prepared. Such systems exist but the fluid is invariably toxic and corrosive. Gamma ray tomography is being used to obtain air core information in a DMC at the JKMRC (Subramanian, 2002), but the technique requires considerable care because of the radiation hazard.

CFD studies on cyclone separators have been reviewed by Suasnabar (2000) and also by Slack et al (2000). The seminal CFD study is that of Hsieh (1988) with further publications by co-workers (Hsieh and Rajamani, 1991, Monredon et al., 1992). These studies used 2d axi-symmetric grids with an imposed air core position. However even with these limitations the work demonstrated the effect of swirl and flow reversal on turbulence behaviour and it is now generally accepted that *k-epsilon* turbulence models will not model these effects effectively. The more complex Reynolds Stress Turbulence model (Launder et al, 1975), is recognized as being more suitable and has been used successfully in recent CFD studies of cyclones. (Suasnabar, 2000 and Slack et al., 2000)

The JKMRC has completed initial CFD studies of dense medium and classifying cyclones cyclones using Fluent (Brennan et al, 2002). The centre is using gamma ray tomography to measure density profiles in dense medium cyclones (Subramanian 2002) and the results from this experimental work are being used to validate the CFD modelling. The initial CFD work was a 3d simulation of a 350mm Dutch State Mines (DSM) pattern body using Fluent. This was a two phase simulation (air/water) and predicted the position of the air core and flow splits with reasonable accuracy. The work used the Volume of Fluid model (VOF) (Hirt and Nichols 1981) to predict the position of the air core and the Fluent implementation of the Reynolds Stress Turbulence model (Launder et al 1975).

In this paper we report the results of the extension of this work to multiphase flows using the Algebraic Slip Mixture model (ASM) (Maninnenn and Taivassalo, 1996) to model the dispersed phases and the air core. The work is being used to model medium segregation in dense medium cyclones and classification in classifying cyclones.

MODEL DESCRIPTION

Mathematical Model

The multiphase simulations used the ASM model (Manninen and Taivassalo 1996) to model particulate solids and the air core. The ASM model solves the Reynolds Averaged Navier Stokes equations for the fluid mixture (derived using Favre averaging) and solves an additional transport (continuity) equation for the volume fraction of each dispersed phase present in the system:

$$\frac{\partial}{\partial t}\alpha_k + \nabla\cdot(\alpha_k \mathbf{u_m}) + \nabla\cdot(\alpha_k \mathbf{u}_{km}) = 0 \qquad (1)$$
$$\mathbf{u}_{km} = \mathbf{u_k} - \mathbf{u_m}$$

$\mathbf{u_{km}}$ is the drift velocity of the phase k relative to the velocity of the mixture $\mathbf{u_m}$, which is determined from the mixture RANS and continuity equations. This is determined from the slip velocities of all dispersed phases relative to the continuous phase (in this case water) $\mathbf{u_{lc}}$:

$$\mathbf{u_{mk}} = \mathbf{u}_{kc} - \sum_{l=1}^{n} \frac{\alpha_k \rho_k}{\rho_m} \mathbf{u}_{lc} \qquad (2)$$
$$\mathbf{u}_{kc} = \mathbf{u}_k - \mathbf{u}_c$$

Manninnen and Taivassalo (1996) calculate $\mathbf{u_{kc}}$ from a force balance on the dispersed phase k, where the momentum transfer to the phase is found by subtracting the phase k momentum equation from the mixture momentum equation and making the assumption that momentum transfer is at local equilibrium:

$$\frac{1}{2}\rho_c A_k C_d |\mathbf{u}_{kc}| \mathbf{u}_{kc} =$$
$$V_k(\rho_k - \rho_m)\left(\mathbf{g} - (\mathbf{u_m}\cdot\nabla)\mathbf{u_m} - \frac{\partial \mathbf{u_m}}{\partial t}\right) + \qquad (3)$$
$$\frac{V_k}{\alpha_k}\left(\alpha_k \nabla\cdot(\alpha_c \tau_{tk}) + \alpha_k \nabla\cdot(\alpha_k \tau_{tc})\right) + \mathbf{M_p}'$$

The equation for $\mathbf{u_{kc}}$ contains the turbulent stresses for both the phase k and the continuous phase c and, also a fluctuating component for the interphase momentum transfer $\mathbf{M_p}'$. The Fluent implementation of the ASM model assumes that these terms are zero and hence cannot model turbulent diffusion of any dispersed phases.

The ASM model cannot models flows where there is a strong departure from local equilibrium in the interphase momentum transfer, however it is computationally much less intensive than a full Eulerian multiphase simulation.

The standard Fluent implementation of the RSM model was used for turbulence closure.

Grid, Boundary Conditions, Problem Set Up

The simulations used Fluent V6 with three dimensional grids and an accurate geometric model of the cyclone body consisting of the feed port, main body and vortex finder. The grids were generated using Gambit using Gambit's Cooper meshing facility, however the grids have been set up so that in the main body they were essentially a cylindrical O grid. Simulations for two cyclones are reported here; (i) a 350mm DSM pattern dense medium cyclone body (78000 grid points) and (ii) a 480mm commercial design cyclone body. (129000 grid points). The feed port used a velocity inlet boundary condition, whilst the underflow and overflow were pressure outlet boundary conditions. The simulations used second order up-winding.

The ASM was used to model medium only in the dense medium cyclone and coal in the classifying cyclone. The dense medium cyclone simulations assumed that the medium solids had a density of 5000 kg.m^{-3} and a single particle size of 30 μm (typical for magnetite). The classifying cyclone simulations assumed the particles were coal with a density of 1350 kg.m^{-3}, however a feed with x size fractions was used where each size fraction was treated as a separate phase.

The ASM was also used to model the position of the air core, where the air is treated as another dispersed phase. This may seem controversial; however the air drift velocity is only non zero in the region of the free surface, where the numerical models generate a zone where the volume fraction of air is greater than zero but less than one. In the CFD cyclone models, the swirl generates a buoyancy force which is normal to the free surface and this in turn generates a drift velocity for the air which is radially inward. This forces the air and water phases to segregate in grid points which lie across the simulated free surface and has the effect of sharpening up the resolution of the free surface of the water as effectively as do the Geo-reconstruct and Donor Acceptor schemes, if the alternative Volume of Fluid (VOF) model is used.

The problems were set up by first obtaining convergence for a water only case. An air core was then allowed to develop by setting the backflow air volume fraction to unity on the overflow and underflow boundary conditions. Finally the feed was changed from water to slurry. This convergence strategy used the unsteady solver and the simulations, particularly for the classifying cyclone simulations, were extremely time consuming with run times of a several weeks on the University of Queensland Silicon Graphics Origin 3000 computer.

RESULTS

Dense Medium Cyclone Simulations

Figure 1 shows a comparison between the contours of slurry density as predicted by CFD and those measured by gamma ray tomography (Subramanian 2002). The results from gamma ray tomography show that the medium segregates with the highest medium concentration at the bottom of the cyclone and in the central region between the air core and the wall. The CFD predictions are similar but the CFD predicts that the medium is more concentrated near the wall at the bottom of the conical section. Secondly the CFD predicts a ring of high medium density directly below the vortex finder. This is shown more clearly in plan in Figure 2. This ring of high density clearly occurs but the density predicted by the CFD is higher being around 1400 kg.m^{-3} compared to a measured peak of around 1300 kg.m^{-3}.

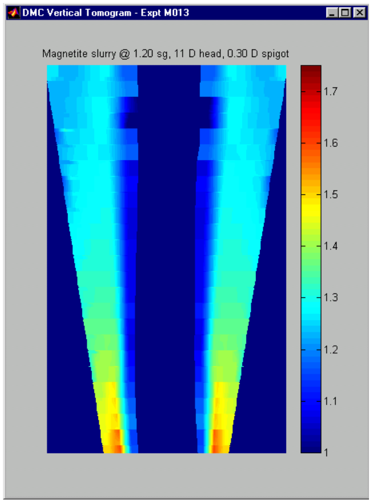

Figure 1a – Density profiles in elevation of 350mm dense medium cyclone at feed density of 1245 kg.m^{-3} and a feed flow rate of 0.0118 m^3.s^{-1}. Measured by Gamma Ray Tomography (Subramanian 2002)

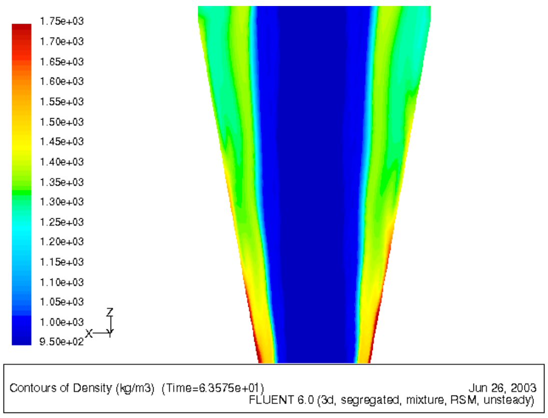

Figure 1b – Density profiles in elevation of 350mm dense medium cyclone predicted by Fluent for the same feed conditions as in Figure 1b.

Finally the CFD predicts that the density drops to that of water near the air/water interface. That is the medium segregates such that a film of nearly pure water forms around the air core. However the tomography measurements show that the density in this region is higher at around 1100 to 1300 kg.m^{-3}. This is shown in Figure 2 and also more clearly in Figure 3. The result of this is that the CFD under predicts the concentration of medium in the overflow and thus over predicts medium segregation.

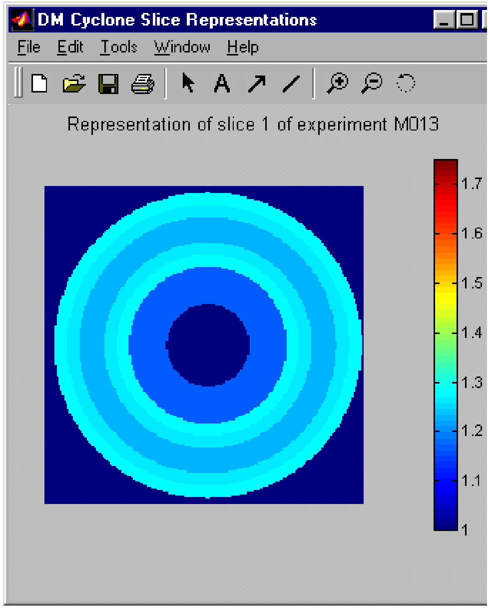

Figure 2a – Density profiles in plan at 10mm above conical section of 350mm dense medium cyclone at feed density of 1245 kg.m^{-3} and a feed flow rate of 0.0118 m^3.s^{-1}. Measured by Gamma Ray Tomography (Subramanian 2002)

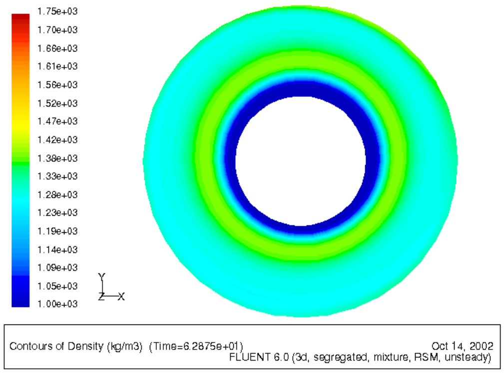

Figure 2b – Density profiles in plan at 10mm above conical section of 350mm dense medium cyclone predicted by Fluent for the same feed conditions as in Figure 2b

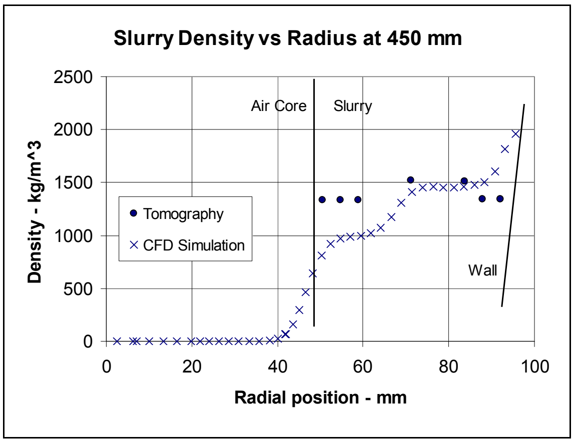

Figure 3 – Dense medium cyclone – Comparison between predicted and measured density as a function of radial position at 450 mm below the cylindrical section

Figure 4 shows a comparison between predicted and measured, overflow and underflow densities as a function of feed flow rate. With the exception of the underflow density at a feed flow rate 0.0188 $m^3.s^{-1}$, the CFD consistently over predicts the underflow density and under predicts the overflow density; that is the CFD over predicts medium segregation.

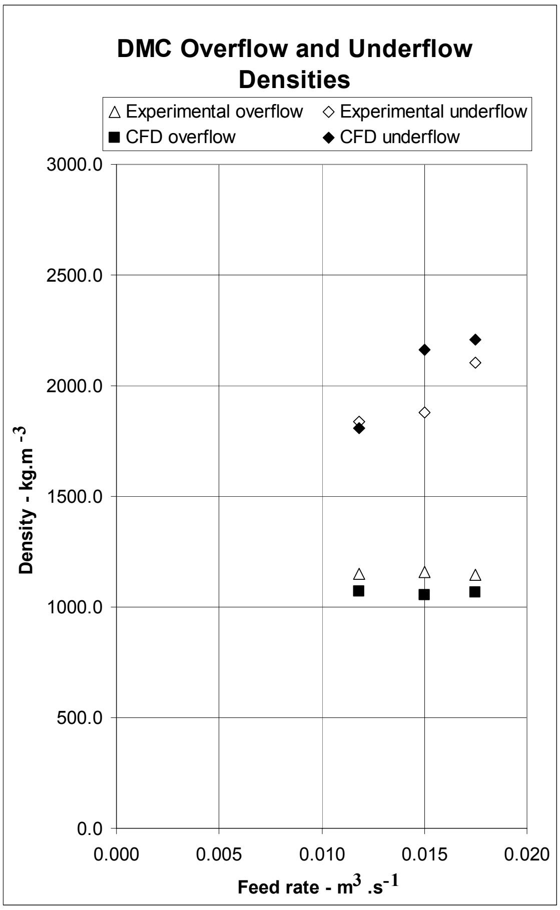

Figure 4 – Dense medium cyclone - Comparison between predicted and measured overflow and underflow densities as a function of feed rate for a feed density of 1240 $kg.m^{-3}$.

The are several possible reasons for this. Firstly the basic ASM model in Fluent does not include the turbulent stresses or other fluctuating terms in the slip velocity calculation. Calculations based on correlations for the ratio of the turbulent diffusivity of the particles to that of a passive scalar (Loth, 2001, Csanady, 1963) would suggest that medium should have the same turbulent diffusivity as a passive scalar. Hence inclusion of the turbulent diffusion term should have some effect in overcoming the segregation effect due to the swirl induced centrifugal force and this may mix the medium up to the free surface. Work is underway to identify whether this is significant or not.

Secondly it should also be noted that the prediction of the position of the free surface between the liquid phase and the air core is somewhat diffuse in these simulations with the region where the air volume fraction is greater than zero and less than one, extending over several radial mesh points. Improving the resolution of the air core may influence the disposition of the medium in the simulated flow.

Finally there may be a lift force in the wall boundary layer which has a shear thinning effect and which is not considered in the simulations. This shear thinning effect may explain why the region of highest medium density is away from the wall in the experimental results.

Classifying Cyclone Simulation

This simulation was conducted at a feed flow rate of 54 $kg.s^{-1}$ with an overall coal concentration in the feed of 12.1% and a solids density of 1350 $kg.m^{-3}$. Figure 5 compares the partition curve predicted for by the CFD simulations to partition curves generated from plant data (at a lower feed concentration of 7.1% solids). As can be seen the partition curves compare extremely well, except that the CFD results over predict the fraction to underflow at 0.033 mm. This may be due to the lower feed concentration in the plant data and further CFD runs are being conducted at the lower feed concentration to verify this.

It is apparent that the absence of the turbulent stresses and other fluctuating terms in the Fluent implementation of the ASM slip calculation does not in this instance affect the prediction of the cut point for the classifying cyclone, whereas these terms may be more important in modelling the medium segregation in dense medium cyclones. The medium in a dense medium cyclone has a much smaller particle size (~30 μm) and it may be that the turbulent mixing of the dispersed phases is more significant at smaller particle sizes.

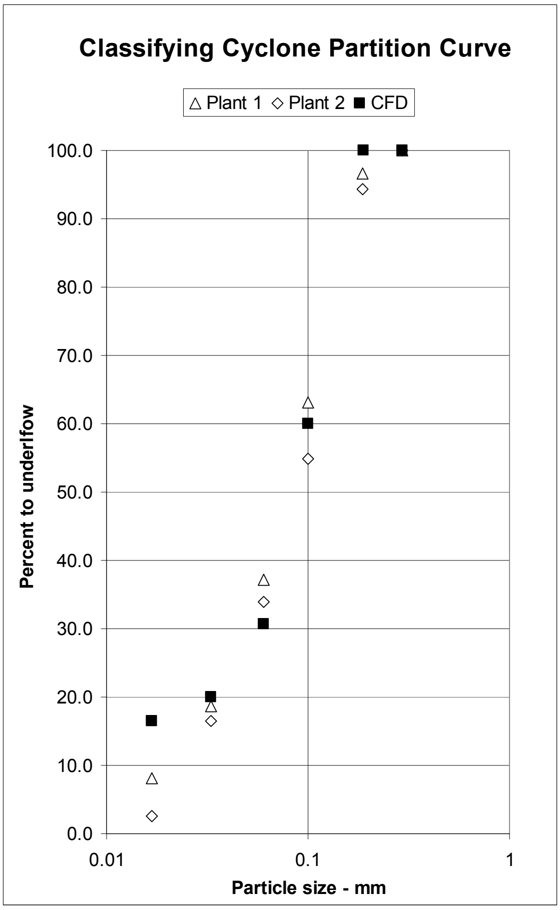

Figure 5 – Partition curve for 480 mm classifying cyclone compared to measured plant behaviour.

CONCLUSIONS

Multiphase simulations of dense medium and classifying cyclone have been conducted in Fluent, using the Algebraic Slip Mixture Model (Manninen and Taivassalo 1996) to model the dispersed phases and the air core, and the Reynolds Stress Model for turbulence closure.

Dense medium cyclone simulations show qualitatively sensible density profiles but the medium segregation is larger compared with segregation measured experimentally by gamma ray tomography. It is possible that this arises because the Fluent implementation of the ASM drift calculation does not include the turbulent stresses or other fluctuating terms as are included in Manninen and Taivassalo's (1996) original derivation of the ASM model. Other factors such as shear thinning at the wall and improved resolution of the free surface between the liquid phase and the air may also have an effect. Investigations are underway to clarify these effects.

Simulations of a classifying cyclone using the ASM approach to model each size range in the feed gave good prediction of the partition curve. In this case the absence of the turbulent stresses and fluctuating terms does not unduly influence the prediction of the partition curve.

REFERENCES

BRENNAN, M. S, HOLTHAM, P. N., RONG, R., LYMAN, G. J., (2002), "Computational fluid dynamic simulation of dense medium cyclones", *Proceedings 9th Australian Coal Preparation Conference, Yeppoon Australia, 13-17 October 2002, Paper B3.*

CHAOUKI, J., LARACHI, F., DUDOKOVIC, M. P., (1997), "Noninvasive Tomographic and Velocimetric Monitoring of Multiphase Flows", *Industrial and Engineering Chemistry – Research*, **36,** 4476-4503.

CSANADY, G. T., (1963), "Turbulent diffusion of heavy particles in the atmosphere.", *J Atmos. Sci,* **20,** 201-208.

HIRT, C. W., NICHOLS, B. D., (1981), "Volume of fluid (VOF) method for the dynamics of free boundaries", *Journal of Computational Physics,* **39**, 201-225.

HSIEH, K. T., (1988), *A phenomenological model of the hydrocyclone,* Ph D Thesis, University of Utah.

HSIEH, K. T., RAJAMANI, R. K., (1991), "Mathematical model of the hydrocyclone based on the physics of fluid flow", *AIChE Journal*, **37**, 735.

LAUNDER, B. E., REECE, G. J., RODI, W. (1975), "Progress in the development of a Reynolds-stress turbulence closure", *Journal of Fluid Mechanics*, **68**, 537-566.

LOTH, E., (2001) "An Eulerian turbulent diffusion model for particles and bubbles", *Internation Journal of Multiphase Flow,* **27,** 1051-1063

MANNINEN M., TAIVASSALO V. (1996), *On the Mixture model for multiphase flow,* Valtion Teknillinen Tutkimuskeskus, Espoo, Finland.

MONREDON T. C., HSIEH K. T., RAJAMANI R. K. (1992), "Fluid flow of the hydrocyclones: An investigation of the device dimensions", *International Journal of Mineral Processing,* **35**, 65-83.

SUASNABAR D. J. (2000), *Dense Medium Cyclone Performance, Enhancements via computational modeling of the physical process,* Ph D Thesis, University of New South Wales.

SLACK, M. D., PRASAD, R. O., BAKKER A., BOYSAN, F. (2000), "Advances in cyclone modeling using unstructured grids", *Trans. IChemE*, **78(A),** 1098-1104.

SUBRAMANIAN, V. S., (2002), *Measuring medium segregation in the dense medium cyclone using gamma ray tomography,* PhD Thesis, JKMRC, University of Queensland.