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# LARGE EDDY SIMULATION OF A DENSE MEDIUM CYCLONE - PREDICTION OF MEDIUM SEGREGATION AND COAL PARTITIONING

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## ABSTRACT

Large Eddy simulations coupled with the mixture model and lagrangian particle tracking has been applied to the study of medium segregation and coal particle partitioning in a dense medium cyclone using Fluent. The mixture model was modified with corrections for wall lift forces, hindered settling, slurry rheology and particle interactions. Predicted velocity profiles are in agreement with the experimental data of Fanglu and Wenzhen (1987), measured by laser doppler anemometry. Predicted density profiles are close to gamma ray tomography data, showing a density drop near the wall. The turbulence analysis showed that the change in the body shape from cylindrical to the conical section is one of the sources for the turbulence inside the cyclone. Once correct medium segregation was predicted, the performance characteristics of the DMC on coal were modelled using Lagrangian particle tracking for particles ranging in size from 0.5 to 4 mm. The predicted Ep values are very close to the experimental values although a slight deviation in the cut-point predictions was observed.

## NOMENCLATURE

**Greek symbols**

$\alpha$ volume fraction
$\rho$ density kg.m$^{-3}$
$\varepsilon_{ijk}$ permutation tensor
$\tau_{ij}$ stress tensor kg.m$^{-1}$.s$^{-2}$
$\omega_j$ rotation or vorticity vector
$\mu$ viscosity kg.m$^{-1}$.s$^{-1}$

**Other symbols**

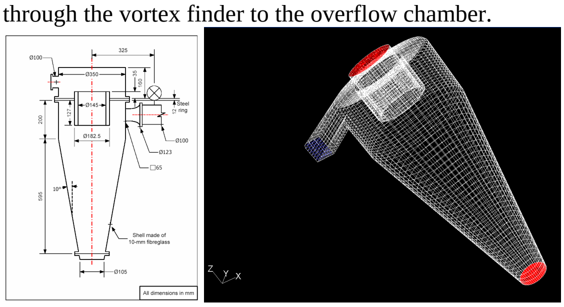
$C_d$ drag coefficient
$C_{lp}$ lift coefficient
$d$ particle or phase diameter - m
$D_c$ cyclone diameter – m
$E_p$ cyclone efficiency parameter
$f_{rep}$ drag correction
$F_{lpi}$ lift force on particle - N
$g_i$ gravity - m.s$^{-2}$
$k_d$ fluid particle exchange coefficient
$P_g$ Granular pressure - pa
$Re$ Reynolds number
$t$ time - s
$x_i$ co-ordinate $i$- m
$u_i$ velocity - m.s$^{-1}$

**Subscripts**

$c$ continuous phase
$d$ discrete (coal) phase
$m$ mixture
$p$ particulate (medium) phase

## INTRODUCTION

Dense medium cyclones are designed to partition coal particles based on particle density with the cut density adjusted by adding a finely dispersed heavy medium to the feed and adjusting the feed medium concentration. In a typical DMC, illustrated in Figure 1, a mixture of medium and raw coal enters tangentially near the top of the cylindrical section, thus forming a strong swirling flow. The denser high ash particles move along the wall of the cyclone due to the centrifugal force, where the velocity is downward and is discharged through the underflow orifice or the spigot. The lighter low ash coal moves towards the longitudinal axis where a strong up flow exists and passes through the vortex finder to the overflow chamber.



(a) (b)

**Figure 1.** Detailed dimensional drawing of the 350 mm DSM dense medium cyclone used for simulations, (b) Grid generated in Gambit.

The presence of medium, coal particles, swirl and the fact that DMCs operate in the turbulent regime makes the flow behavior complex and studying the hydrodynamics of DMCs using Computational Fluid Dynamics (CFD) is a valuable aid to understanding their behaviour.

Most of the CFD studies have been conducted for classifying hydrocyclones (Davidson, 1994; Hsieh, 1988; Slack et al 2000; Narasimha et al 2005 and Brennan, 2006). CFD studies of DMCs are more limited (Zughbi et al, 1991, Suasnabar (2000) and Brennan et al, 2003, Narasimha et al (2006)). DMCs and Classifying cyclones are similar geometrically and the CFD approach is the same with both. A key problem is the choice of turbulence model. The turbulence is too anisotropic to treat with a k-e model and this has led some researchers to use the differential Reynolds stress turbulence model. However some recent studies (Slack et al, 2000; Delagadillo and Rajamani, 2005; Brennan, 2006) have shown that the LES technique gives better predictions of the velocities in cyclones and seems to do so on computationally practical grids.

In this paper, CFD studies of multiphase flow in 350mm and 100mm Dutch State Mine (DSM) dense medium cyclone are reported. The studies used FLUENT with 3d body fitted gird and used the mixture model to model medium segregation, with comparisons between Large Eddy Simulation (LES) and Differential Reynolds Stress Model (DRSM) turbulence models. Predictions are compared to measured concentrations by GRT (Gamma ray tomography) and overall simulated performance characteristics using Lagrangian particle tracking for particles were compared to experimental data.

## MODEL DESCRIPTION

### *Turbulence Models*

The basic CFD approach was the same as that used by Brennan (2003). The simulations used Fluent with 3d body fitted grids and an accurate geometric model of the 350mm DSM pattern dense medium cyclone used by Subramanian (2002) in his GRT studies. The dimensions of the cyclone are shown in Figure 1a and a view of the grid used in the simulations is shown in Figure 1b. The equations of motion were solved using the unsteady solver and represent a variable density slurry mixture:

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial \rho_m u_{mi}}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho_m u_{mi}) + \frac{\partial}{\partial x_j}(\rho_m u_{mi} u_{mj}) = -\frac{\partial}{\partial x_i} p + \frac{\partial}{\partial x_j}(\tau_{\mu,ij} + \tau_{d,ij} + \tau_{t,ij}) + \rho_m g_i \qquad (2)$$

The RANS simulations were conducted using the Fluent implementation of the Launder et al (1975) DRSM model with the Launder linear pressure strain correlation and LES simulations used the Fluent implementation of the Smagorinsky (1966) SGS model. In the DRSM simulations $\tau_{t,ij}$ in equation (2) denotes the Reynolds stresses , whilst in the LES simulations $\tau_{t,ij}$ denotes the sub grid scale stresses. $\tau_{d,ij}$ is the drift tensor and arises in equation (2) as part of the derivation of the Mixture model (Manninenn et al 1996). The drift tensor accounts for the transport of momentum as the result of segregation of the dispersed phases and is an exact term:

$$\tau_{d,ij} = \sum_{p=1}^{n} \alpha_p \rho_p u_{pm,i} u_{pm,j} \qquad (3)$$

All equations were discretized using the QUICK option except that Bounded central differencing was used for momentum with the LES. PRESTO was used for Pressure and SIMPLE was used for the pressure velocity coupling. The equations were solved with the unsteady solver with a time step which was typically $5.0 \times 10^{-4}$s for both the DRSM simulations and LES simulations. The LES used the Spectral Synthesiser option to approximate the feed turbulence.

### *Multiphase modeling – mixture model with lift forces*

The medium was treated using the Mixture model (Manninnen et al 1996), which solves the equations of motion for the slurry mixture and solves transport equations for the volume fraction for any additional phases *p*, which are assumed to be dispersed throughout a continuous fluid (water) phase *c*:

$$\frac{\partial}{\partial t}\alpha_p + \frac{\partial}{\partial x_i}(\alpha_p u_i) + \frac{\partial}{\partial x_i}(\alpha_p u_{pm,i}) = 0 \qquad (4)$$

$$u_{pm,i} = u_{pi} - u_i$$

$u_{pm,i}$ is the drift velocity of the *p* relative to the mixture *m*. This is related to the slip velocity $u_{pc,i}$, which is the velocity of the *p* relative to the continuous water phase *c* by the formulation:

$$u_{pmi} = u_{pci} - \sum_{l=1}^{n} \frac{\alpha_k \rho_k}{\rho_m} u_{lci} \qquad (5)$$

$$u_{pci} = u_{pi} - u_{ci}$$

Phase segregation is accounted for by the slip velocity which in Manninen et al's (1996) treatise is calculated algebraically by an equilibrium force balance and is implemented in Fluent in a simplified form. In this work Fluent has been used with the granular options and the Fluent formulation for the slip velocity has been modified where (i) a shear dependent lift force based on Saffman's (1965) expression and (ii) the gradient of granular pressure (as calculated by the granular options) have been added as additional forces. Adding the gradient of granular pressure as an additional force effectively models Bagnold dispersive forces (Bagnold 1954) and is an enhancement over our earlier work (Narasimha et al, 2006).

$$u_{pci} = \frac{d^2{}_p(\rho_p - \rho_m)}{18 f_{rep} \mu_c} * \begin{pmatrix} g_i - \frac{\partial}{\partial t} u_{mi} - u_{mj} \frac{\partial}{\partial x_j} u_{mi} + \\ 0.75 \frac{\rho_c}{\rho_p - \rho_m} C_{lp} \varepsilon_{ijk} \omega_{mj} u_{pck} - \frac{1}{\alpha_p(\rho_p - \rho_m)} \frac{\partial}{\partial x_i} P_{pg} \end{pmatrix} \qquad (6)$$

Equation (6) has been implemented in Fluent as a custom slip velocity calculation using a user defined function. $f_{rep}$ has been modelled with the Schiller Naumann (1935) drag law but with an additional correction for hindered settling based on the Richardson and Zaki (1954) correlation:

$$f_{rep} = \left(1 + 0.15 \mathrm{Re}_p^{\;0.687}\right) \alpha_p^{\;-4.65} \qquad (7)$$

The lift coefficient has been calculated as

$$C_{lp} = 4.1126 \left( \frac{\rho_f d_p^{\;2} |\omega|}{\mu_c} \right) f_c \qquad (8)$$

$f_c$ corrects the lift coefficient using the correlation proposed by Mei (1992).

### *Medium rheology*

The mixture viscosity in the region of the cyclone occupied by water and medium has been calculated using the granular options where the Gidaspow et al (1992) granular viscosity model was used. This viscosity model is similar to the Ishii and Mishima (1984) viscosity model used in earlier work (Narasimha et al 2006) in that it forces the mixture viscosity to become infinite when the total volume fraction of the medium approaches 0.62 which is approximately the packing density and has the effect of limiting the total medium concentration to less than this value. However the Gidaspow et al model (1992) also makes the viscosity shear dependant.

#### *Medium with size distribution*

The mixture model was set up with 8 phase transport equations, where 7 of the equations were for medium which was magnetite with a particle density of 4950 kg.m$^{-3}$ and 7 particle sizes which were; 2.4, 7.4, 15.4, 23.8, 32.2, 54.1 and 82.2 μm. The seventh phase was air, however the slip velocity calculation was disabled for the air phase thus effectively treating the air with the VOF model (Hirt and Nichols 1981). The volume fraction of each modeled size of medium in the feed boundary condition was set so that the cumulative size distribution matched the cumulative size distribution of the medium used by Subramanian (2002) and the total feed medium concentration matched Subramanian's (2002) experimental feed medium concentrations.

#### *Coal particle tracking model*

In principle the mixture model can be used to model the coal particles as well as medium but the computational resources available for this work limited simulations using the mixture model to around 9 phases, and it was impractical to model coal with more than two sizes or densities simultaneously with 6 medium sizes. Thus the Fluent discrete particle model (DPM) was used where particles of a known size and density were introduced at the feed port using a surface injection and the particle trajectory was integrated through the flow field of a multiphase simulation using medium. This approach is the same as that used by Suasnabar (2000).

Fluent's DPM model calculates the trajectory of each coal particle *d* by integrating the force balance on the particle, which is given by equation (10):

$$\frac{Du_{d,i}}{dt} = k_d\left(u_{m,i} - u_{d,i}\right) + g_i\left(\frac{\rho_d - \rho_m}{\rho_d}\right) \qquad (9)$$

$k_d$ is the fluid particle exchange coefficient:

$$k_d = \left(\frac{18\mu_m d_d^2}{\rho_d}\right)\left(\frac{C_D \operatorname{Re}_d}{24}\right) \qquad (10)$$

The presence of medium and the effects of medium segregation are incorporated in the DPM simulations because the DPM drag calculation employs the local mixture density and local mixture viscosity which are both functions of the local medium concentration. This intrinsically assumes that the influence of the medium on coal partitioning is a primarily continuum effect. i.e., the coal particles encounter (or "see") only a dense, high viscosity liquid during their trajectory. Further the DPM simulations intrinsically assume that the coal particles only encounter the mixture and not other coal particles and thus assume low coal particle loadings.

To minimize computation time the DPM simulations used the flow field predicted by the LES at a particular time. This is somewhat unrealistic and assumes one way coupling between the coal particles and the mixture.

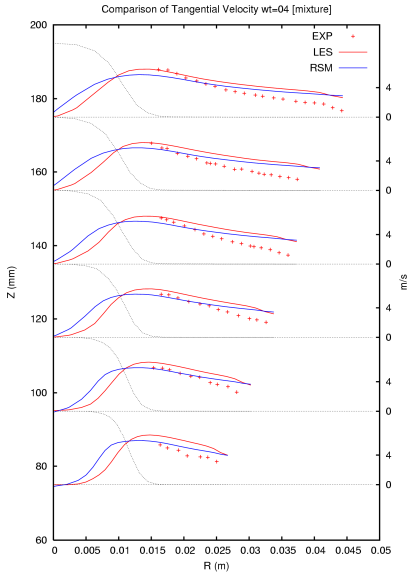
## RESULTS

### *Velocity Predictions*

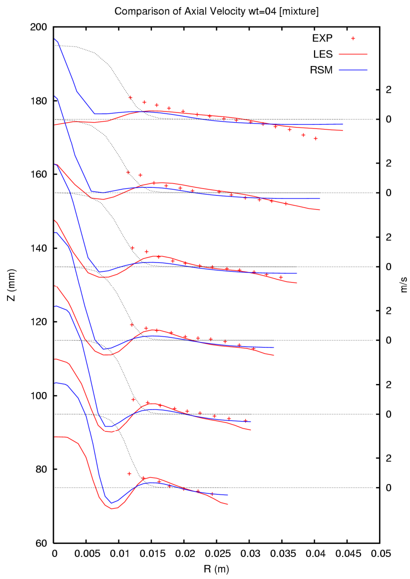
The predicted velocity field inside the DSM geometry is similar to velocities predicted in DMCs by Suasnabar (2000). Predicted flow velocities in a 100mm DSM body were compared with experimental data (Fanglu and Wenzhen (1987)) and shown in Fig 2(a) and 2(b). Predicted velocity profiles are in agreement with the experimental data of Fanglu and Wenzhen (1987), measured by laser doppler anemometry.

### *Air core predictions*

Figure 3 shows a comparison between the air core radius predicted from LES and DRSM simulations and the air core measured by Subramanian (2002) by GRT in a 350mm DSM body.




(a)




(b)

**Figure 2.** Comparison of predicted (a) tangential velocity field, (b) axial velocity field with experimental data (Fanglu and Wenzhen (1987))

In particular Figure 3 shows that the air core position is predicted more accurately by the LES and that the radius predicted by the RSM is smaller than experimental measurements in the apex region. This is consistent with velocity predictions because a lower prediction of the tangential velocity (as predicted by the DRSM) should lead to a thicker slurry/water region for the same slurry/water feed flow rate and therefore a thinner air core. This lends some cautious credibility to the LES velocity predictions.

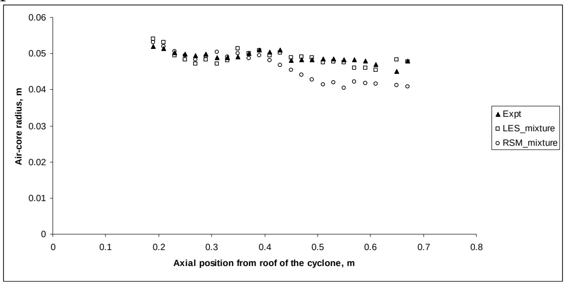



**Figure 3.** Comparison between predicted and measured air core positions

***Turbulence analysis of two phase flow in DSM body***

Using the LES turbulence model, an analysis was made of the two phase (air-water) turbulence in a 350 mm DSM body. Figure 4 shows that in the DSM design, a very high turbulent kinetic energy occurs near the tip of vortex finer. As expected, the sudden transition from the cylindrical body to the conical section is a clear source of turbulent fluctuations down the cyclone body. These fluctuations propagate a very high turbulent kinetic energy near the bottom of the apex zone.

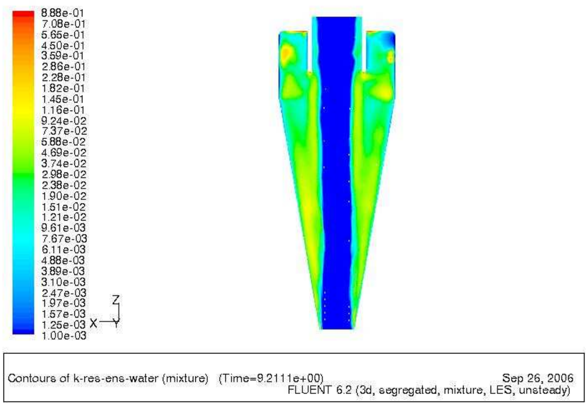
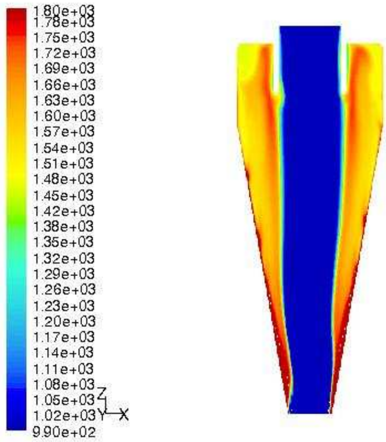



**Figure 4.** Predicted turbulent kinetic energy contours in 350 mm DSM body

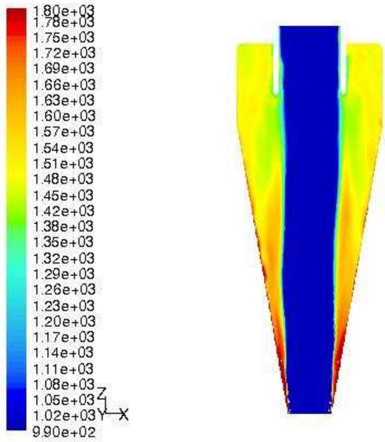
***Prediction of medium segregation using medium feed size distribution, lift forces and viscosity corrections***

Figure 5 shows the density profiles predicted by the CFD at steady flow for a feed RD of 1.465 and a feed head of 9Dc (equivalent to a volumetric flow rate of 0.0105 $m^3.s^{-1}$) together with an experimentally measured density profile for the same feed conditions from Subramanian (2002) . Figure 5a shows the density profile using the modelling approach reported in Brennan (2003) and Brennan et al (2003) which is the basic mixture model with DRSM turbulence, Schiller Naumann drag relationship and a single medium size of 30µm, Figure 5b shows the density profile for the latest work which is from am LES using the mixture-granular model, medium with a feed size distribution, Schiller Naumann drag relationship with hindered settling, Lift and Bagnold forces and the Gidaspow et al (1992) granular viscosity law.

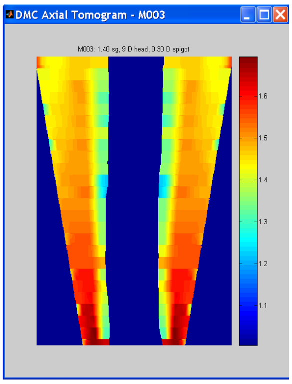
Figure 6 is a graphical comparison of the same data shown in Figure 5 at an elevation of 0.27 m and 0.67 m below the top of the cyclone body. 0.27m is the beginning of the apex and 0.67m is the lowest point at which Subramanian (2002) collected data. The predicted overflow and underflow medium densities are listed in Table 1.




(a) DRSM - Brennan (2003)




(b) LES latest work




(c) Experimental – Subramanian (2002)

**Figure 5.** Comparison between predicted slurry densities (a) DRSM-Mixture from Brennan (2003) (b) LES-Mixture latest work (see text left) (c) Experimental - Subramanian, 2002 for feed RD of 1.465, Feed head = $9D_c$ ($Q_f$ = 0.0105 $m^{-3}.s^{-1}$); in elevation. .

The simulations from earlier work (Brennan 2003, Brennan et al 2003) with the basic mixture model, DRSM, single particle size, no lift and viscosity corrections display excessive medium segregation although some of the characteristics of the distribution of medium are captured even though the predictions are inaccurate. At both 0.27m and 0.67m the medium concentration is excessive in the centre of the slurry region, and increases to a very large concentration at the wall at 0.67m.

The LES with the mixture model enhancements is much more realistic. The improved accuracy however can be attributed to all of the enhancements. The medium used in Subramanian's (2002) GRT studies contained a significant distribution of sizes between 4 and 40 $\mu m$ and one would expect that the smaller size would not segregate to the same degree as the larger size. Hence modeling the medium size distribution is necessary.

| Turbulence model | Overflow, kg.m$^{-3}$ | Underflow, kg.m$^{-3}$ | Recovery to underflow |
|---|---|---|---|
| DRSM | 1194 | 2232 | 0.256 |
| LES | 1339 | 1978 | 0.175 |
| Experimental | 1375 | 2076 | 0.137 |

**Table 1.** Predicted Flow densities and recovery to underflow - (a) DRSM-Mixture from Brennan (2003) (b) LES-Mixture latest work, (c) Experimental from Subramanian (2002) (feed RD of 1.465, Feed head = 9D$_c$, $Q_f = 0.0105$ m$^{-3}$.s$^{-1}$)

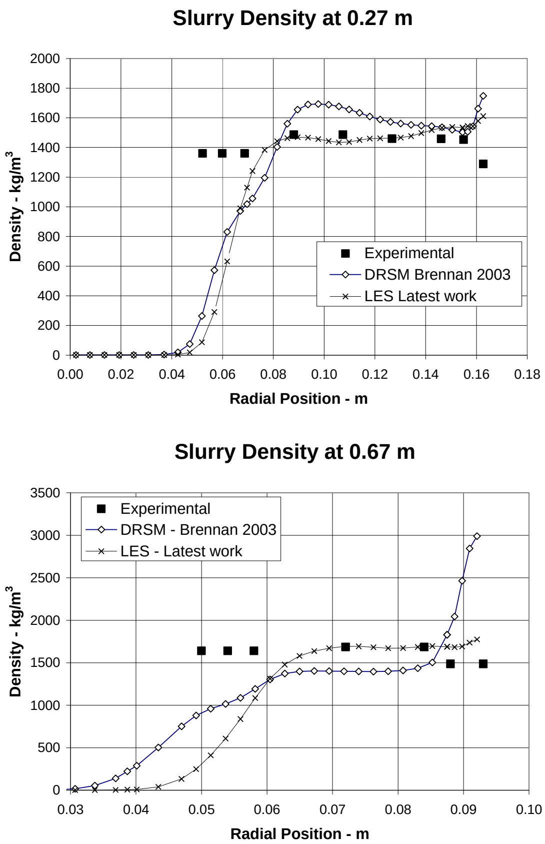



**Figure 6.** Comparison between density contours predicted (LES and RSM models) by CFD and those measured by gamma ray tomography (a) at 0.27m, (b) 0.67m from roof of cyclone (Subramanian, 2002) for feed RD of 1.465.

Finally the LES model is an enhancement over the DRSM turbulence model. This is partly because it is believed that it predicts the tangential velocities more accurately but also because LES resolves the larger scale turbulent fluctuations which generate turbulent mixing of the medium and this mixing is resolved because the instantaneous velocities are passed to the slip velocity calculation.

***Prediction of partition curve-pivot phenomena***

Coal particles are typically in the range of 1100 and 1800 kg.m$^{-3}$ in density and between 0.5 and 8 mm in size. DPM simulations were conducted where particles in this size range were injected at the feed and tracked. Each DPM simulation was repeated 5 times and 1050 particles were injected per simulation. The outlet stream to which each particle deported was noted and the information used to construct partition curves as function of particle density for given particle sizes. Figure 7 shows the partition curves so generated using a multiphase simulation with a feed RD of 1.2 and a feed head of 9D$_c$.

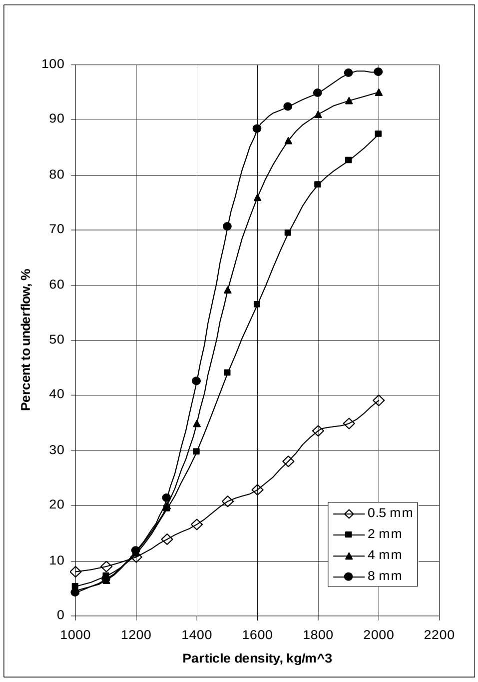



**Figure 7.** Predicted size-by-size partition curves in a 350mm DSM cyclone

As shown in figure 7, for the first time, the pivot phenomenon, in which partition curves for different sizes of coal pass through a common pivot point, has been successfully modelled using CFD. The predicted pivot parameters deviate slightly from the experimental data. The underflow split ratio and feed RD should be 14% and 1.236 from experimental observations whereas the CFD pivot point represents about 12 % underflow flow ratio and pivot point relative density of 1.215.

This comprehensive CFD model of dense medium cyclone is able to predict the performance of the DSM body reasonably well when compared to float-sink data of -2 +0.5 mm sized coal fraction (Hornsby and Wood 2000) (shown in figure 8). In particular, for the given set of design and operating condition, the predicted Ep value is about 0.075, where as float and sink data represents about 0.0625. The predicted Ep values are close to the experimental values although cut-point predictions deviate slightly. It is believed that the cut-point deviations are due to the interaction between coal particle-particles, which drive the extra resistance forces for the particle separation.

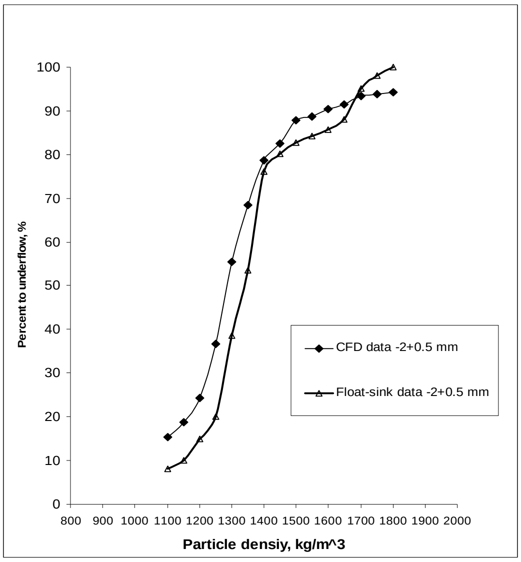



**Figure 8.** Comparison of CFD prediction with float-sink data (Hornsby and Wood (2000), feed density RD =1.3 at 9Dc inlet head) in 350mm DSM.

## CONCLUSION

A large eddy simulation (LES) coupled with the Mxture Model has been applied to the study of medium segregation in a dense medium cyclone. The Mixture model was modified with corrections for wall lift forces, hindered settling, slurry rheology and particle interactions. Predicted velocity profiles are in agreement with the experimental data of Fanglu and Wenzhen (1987), measured by laser doppler anemometry. Predicted density profiles are close to gamma ray tomography data from Subramanian (2002). The two phase turbulence analysis showed that the change in the body shape from cylindrical to the conical section is one of the sources for the turbulence inside the cyclone. Once correct medium segregation was predicted, the performance characteristics of the DMC on coal were modelled using Lagrangian particle tracking for particles ranging in size from 0.5 to 8 mm. The predicted Ep values are very close to the experimental values although a slight deviation in the cut-point predictions was observed.

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