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# DENSE SLURRY CFD MODEL FOR HYDROCYCLONE PERFORMANCE EVALUATION INCORPORATING RHEOLOGY, PARTICLE DRAG AND LIFT FORCES

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## ABSTRACT

Common applications of hydrocyclones include classification, thickening, de-sliming and de-gritting. In all the operations cyclone separators usually operate under high solid loading conditions. Computational Fluid Dynamic (CFD) models developed so far are unable to predict the behavior at high percentage of solids. Therefore, present paper is aimed to develop the CFD model corrected with suitable rheological model, particle drag and lift forces to account particle fluid interactions at high solid volume fractions. Turbulence is resolved using large eddy simulation. Drag is corrected with solids loading; rheology is modelled using Newtonian model corrected with fines. CFD predicted two-phase water split and air-core data is validated against Electrical Resistance Tomography and High Speed Video camera measured data. The influence of feed solids on the air core size also investigated. Multiphase simulations ran with 0-50% feed solid loadings are analyzed and validated in terms of cut size and efficiency. Modified CFD model is able to predict the experimental data with reasonable accuracy. Additional validation in terms of cut size in 250 mm Krebs cyclone (Devulapalli, 1997) is also provided in comparison with discrete phase model and standard mixture model.

**Keywords**: multicomponent, hydrocyclone, VOF, interaction parameter

## INTRODUCTION

Hydrocyclones have become an important equipment for the chemical, mineral, coal and powder processing industries due to the simple design, high capacity, low maintenance, low operating cost and small dimensions of the device. Flow in hydrocyclone is multiphase in nature as it consists of water, air, and particles of different sizes. In addition, the flow is turbulent. Therefore, precise experimental measurements of flow field and flow behavior inside cyclone are difficult and very sparse literature is available till date (Brennan et al., 2007a; Dabir, 1983; Devulapalli, 1997; Hsieh and Rajamani, 1988; Marins et al., 2010; Rakesh et al., 2014). CFD is already proved as a sophisticated tool to investigate the internal flow dynamics (Cullivan et al., 2003; Narasimha et al., 2012; Slack et al., 2000; Vakamalla and Mangadoddy, 2015; Wang et al., 2007). Usage of 2D geometries and isotropic turbulence models (κ-ε, RNG κ-ε) were limited due to the unrealistic predictions (Delgadillo and Rajamani, 2005; Hsieh and Rajamani, 1991; Ma et al., 2000; Narasimha et al., 2005). Reynolds Stress Model (RSM) solving individual stresses was having good predictions with the experiments (Aurelien. et al., 2012; Slack et al., 2000; Wang et al., 2007) compared to κ-ε, Rng κ-ε models. But, by resolving the large scale eddies and modeling the small scale eddies, large eddy simulation (LES) model may be able to simulate highly swirling flows accurately. LES coupled with Volume of Fluid (VOF) model was adopted for accurate prediction of the two phase air-core and flow field in hydrocyclones (Brennan, 2006; Brennan et al., 2007b; Delgadillo and Rajamani, 2005; Teja Reddy et al., 2015). The VOF model is best suited to model CFD problems where there is a clear air/water free surface between a continuous air and a continuous water phase.

Industrial cyclones are treated with high percentage of solids. Therefore, usage of accurate multiphase model along with suitable rheology model is necessary for efficient modelling. CFD multiphase models include the full Eulerian multiphase approach, the simplified Eulerian approaches such as volume of fluid (VOF), Algebraic Slip Mixture model (ASM) and the Lagrangian approach. Full Eulerian-Eulerian approach solves individual continuity and momentum equation for each phase. Whereas, ASM model is a simplified Eulerian model, in which continuity and momentum equations are solved for the mixture and slip velocity is solved for the volume fraction of dispersed phases. Simplified multiphase models are better than the full multiphase models in terms of uncertainties in closure relations and computation timing (Manninen et al., 1996). Although Lagrangian based Discrete Phase Model (DPM) able to show diverse behavior of particles of different sizes and densities, it cannot be used for concentrated slurries as it was tracking dilute particle motion (Delgadillo and Rajamani, 2007; Kraipech et al., 2005). The DPM model does not consider the particle–particle interactions, particle concentrations effect on the flow medium at high concentrated slurries. ASM model in combination with RSM turbulence model has been frequently used for the multiphase flow predictions (Aurelien. et al., 2012; Wang et al., 2007). But, at higher concentration the effect of additional forces (lift, drag, and dispersion) are significant on the particles (Davidson, 1994; Kraipech et al., 2005). As the solids content increases, hindrance from the surrounding particles also increases. A change in the drag is required to account the hinder settling effect of the particles. Therefore, ASM model has to modify with additional forces for accurate predictions, especially at higher concentration. As feed solids concentration increases, a rise in the slurry viscosity is expected; Usage of a viscosity model is therefore important.

This paper discusses the dense slurry behavior (10-50% weight of solids) on the flow properties like volumetric flow rate (Q), water split (Rf), solid split (Rs), cut size (d50) and sharpness of separation (α) from the in-house experiments. Further, effect of spigot on the underflow discharge is also studied. Predictions of modified ASM model with additional forces and rheology modifications are compared with experimental data. Additional validation is also shown in 250 mm Krebs hydrocyclone (Devulapalli, 1997) with 27.2% feed solids concentration.

## MODEL EQUATIONS

### Turbulence models

The CFD approach used here is same as that used by Narasimha et al., (2012), Vakamalla et al., (2014). Unsteady equations of motion for a slurry mixture are solved by using Large Eddy Simulation.

### Multiphase modelling-Mixture model with additional forces and rheological models

Modified mixture model with lift forces developed by Narasimha (2010) is used in simulations. This model accurately predicted HC/DMC performance (Narasimha et al., 2012; Vakamalla and Mangadoddy, 2015). Compared to standard mixture model (Manninen et al., 1996), this model modifies the slip velocity with additional forces. It uses Schiller and Naumann (1935) drag law with an additional correction factor similar to Richardson and Zaki (1954) correlation to account hinder settling of the particles. Newtonian viscosity model corrected with fines (Narasimha et al., 2012) as shown in Equation (1) is used for the rheology predictions. Where, $\mu_m$, $\mu_w$ are mixture and water viscosity and $\alpha_p$ is volume fraction of solids.

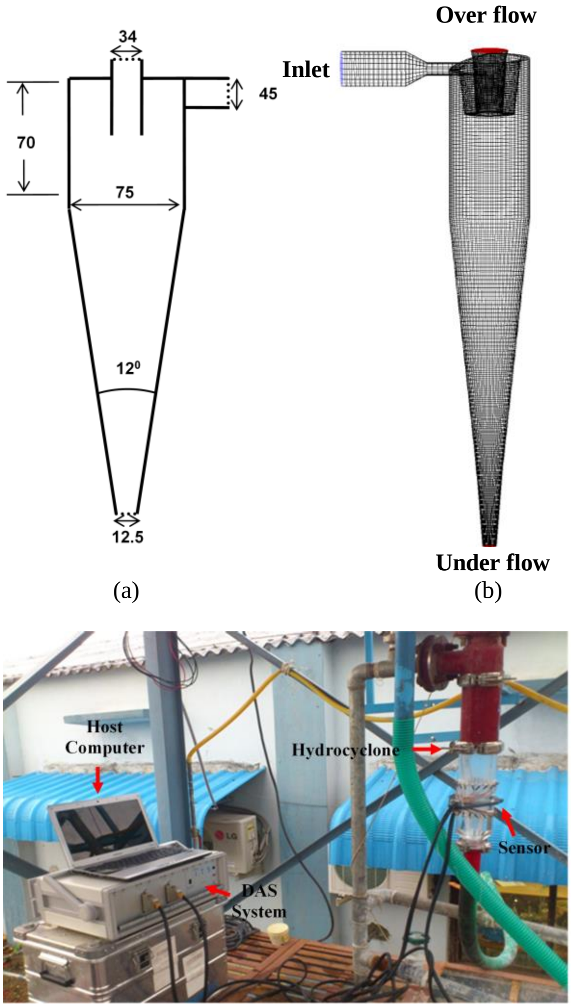
$$\frac{\mu_m}{\mu_w} = \left[1 - \frac{\alpha_p}{0.62}\right]^{-1.55} \left(F_{-38}\right)^{0.39} \qquad (1)$$

| Variable | Variation Range |
|---|---|
| Pressure (psi) | 5, 15, 25 |
| Concentration (wt % of feed solids) | 0, 10, 20, 30, 40, 50 |
| Vortex finder diameter (mm) | 25 |
| Inlet diameter (mm) | 45 |
| Spigot diameter (mm) | 10, 12.5, 15, 17.5 |
| Cyclone diameter (mm) | 75 |

**Table 1:** Range of variable conditions used to study the flow behavior in 75 mm cyclone.

## EXPERIMENTAL SETUP

In the present work, 75 mm hydrocyclone is used to perform the in-house two-phase and multiphase experiments. The test rig used for the experimental studies is shown in Figure 1 (c). Feed flow rate is measured by collecting the samples from the two outlets (underflow and overflow) for 10 seconds in two separate buckets. This process is repeated for 3 times to measure the accuracy of the measurements. After the sample collection from feed, overflow and underflow; small volume of sample is taken to measure the particle size using Microtrac S3500 particle size analyser. Remaining sample is kept for drying to measure the water recovery to the underflow ($R_f$) and solids recovery to the underflow ($R_s$). $R_f$ and $R_s$ values are further used in the whiten equation (Napier-Munn et al., 1996) to fit the sharpness of separation (α) and cut size ($d_{50}$). Additional experimental data on the air core is generated using high speed ITS z800 Electrical Resistance Tomography (ERT) system with a data acquisition speed of 1000 dual frames per second and High Speed Video camera (HSVC) with 10x optical zoom at 30 fps at 1280 X 720 pixels for the purpose of CFD validation. The procedure for air core data processing by ERT and HSVC is explained in the author's previous work (Rakesh et al., 2014). Variables used to study the flow behavior in a 75 mm hydrocyclone are shown in Table 1.




(c)

**Figure 1:** 75mm hydrocyclone (a) schematic diagram and (b) mesh used for simulation and (c) test rig used for the experimental studies.

## NUMERICAL MODELLING

CFD studies are undertaken using ANSYS's Fluent 13 in a 75 mm conventional cyclone which is used to run the solids experiments. A 3D fitted grid with 300k nodes is used. Grid dependence has been checked and presented in the paper Vakamalla et al. (2014). A detail of the geometry and grid used for the simulation is given in Figure 1 (a), (b). Feed size distribution of silica considered for the multiphase simulations are 3.35, 10.25, 19.37, 28.27, 38, 63, 90 µm with a density of 2650 kg/m$^3$. Initially free surface between air and water (air core) is resolved using VOF model. Multiphase model is changed to modified ASM model before introducing silica. Turbulence is modelled using Large Eddy Simulation (LES). A bounded central differencing scheme is used to discretise momentum equations. Pressure is solved by using PRESTO. QUICK is used to solve dispersed phase transport equations. Fixed time step of $1.0 \times 10^{-5}$ s is used. Inlet is set to Pressure and outlet has been set to velocity boundary condition. Air back volume fraction of 1.0 is used on the overflow and underflow which enables the simulation to generate air core by drawing air so that negative pressure can be maintained in the centre region. Models used in the simulation studies are summarized in Table 2.

| Model type | Model used |
|---|---|
| Multiphase | VOF, ASM and Modified ASM |
| Drag | Schiller Naumann corrected with Richardson and Zaki |
| Lift | Saffman |
| Turbulence | LES |
| Pressure | PRESTO |
| Discretization | QUICK |
| Coupled solver for momentum and continuity | SIMPLE |

**Table 2:** Range of variable conditions used to study the flow behavior in 75 mm cyclone.

## RESULTS

### Experimental

This section discusses the data obtained from the analysis of the feed solids concentration. Figure 2 (a) displays the volumetric flowrate ($m^3$/hr) and underflow solids concentration variation with an increase in the feed solids concentration at a pressure of 15 psi. It can be depicted that, an increase in the feed solids concentration decreases the volumetric flowrate and increases the solids present in the underflow (Narasimha, 2010). As the feed solids content increases more amounts solids start accumulating near the walls of conical section and reduce the flowrate to the underflow. As the feed solids content is increased the amount solids present inside the cyclone also increased, this further improves the underflow solids discharge. A decrease in the solid split and an increase in the water split are observed with an increase in the solids concentration at 15 psi pressure (Figure 2 (b)). The solid fraction associated with the water split travels to the conical wall near the underflow is unable to separate by centrifugal forces. With an increase in the viscosity levels of the slurry, a reduction in fluid speed is expected. This increases the water split to the underflow. An increase in the $R_f$ reduces the solid split to the overflow. Effect of spigot diameter on the flow rate and solids recovery is shown in Figure 3. With an increase in the spigot diameter from 10 mm to 17.5 mm, an increase in the flowrates is observed (Bhaskar et al., 2007). As the spigot diameter increases the outlet flow area available for the fluid discharge also increases. Hence, high flowrates are observed. As the spigot diameter increases the amount of water coming to the underflow increases and a reduction in the underflow solids are observed.

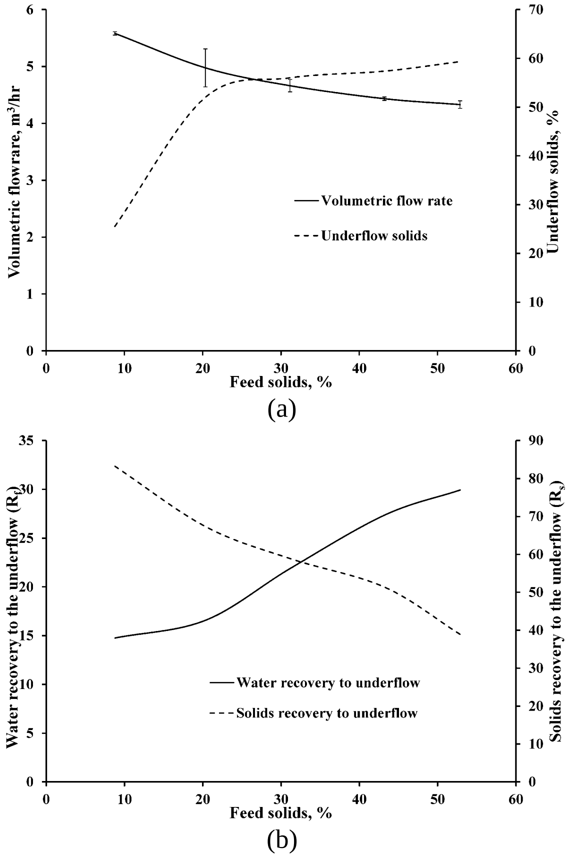



**Figure 2:** (a) Variation of volumetric flowrate ($m^3$/hr) and underflow solids concentration, (b) Variation of water recovery and solids recovery to the underflow with an increase in the feed solids concentration with a 17.5 mm spigot at 15 psi pressure.

### CFD

#### *Two-phase*

Experiments performed in 75 mm hydrocyclone are used to validate the two-phase CFD results. The computations are performed for a spigot diameter of 15 mm at different feed velocities. The mass fluxes for each feed velocity condition are predicted using the reports option in FLUENT software. Mass flow rates at the inlet and two outlets are predicted and water spilt to underflow is calculated. The calculated water spilt to underflow ($R_f$) and air-core diameter measured by Electrical Resistance Tomography (ERT) and High Speed Video imaging (HSV) (Rakesh et al., 2014) is compared with CFD predictions of LES turbulence model coupled with VOF multiphase model. The corresponding plots are displayed in Figure 4. From the Figure 4 (a), it can be depicted that water split predictions of LES model is clearly following the experimental values. LES model is able to predict the pressure variation in the given hydrocyclone. Air-core diameter predictions shown in Fig 4 (b) are also following the experimental trend even though there is a small difference at lower pressure.

#### *Multiphase*

To show the importance of ASM model corrected with rheology and additional forces a case from the literature (Devulapalli, 1997) is undertaken for the CFD studies. A suitable feed size distribution of 4.25, 13.8, 27, 40, 55.4, 110.34 µm for 27.2% feed solids concentration considered. Multiphase simulations ran with DPM, standard ASM and rheology corrected ASM model with lift and drag forces. The corresponding performance curves are displayed in Figure 5. DPM model predictions are completely deviated from the experimental measurements.

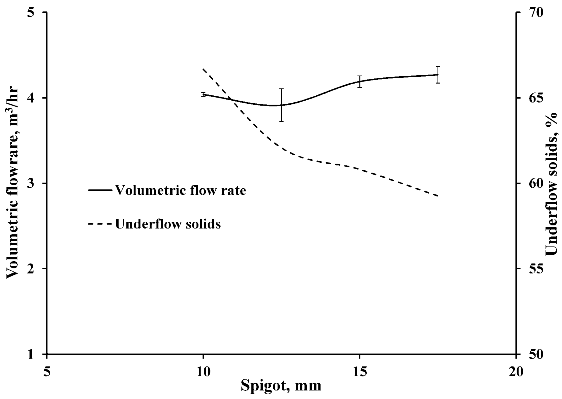
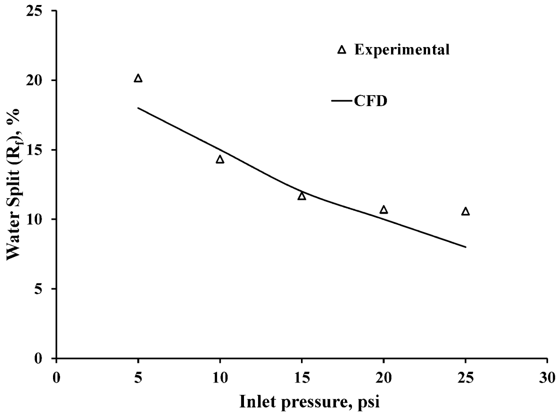
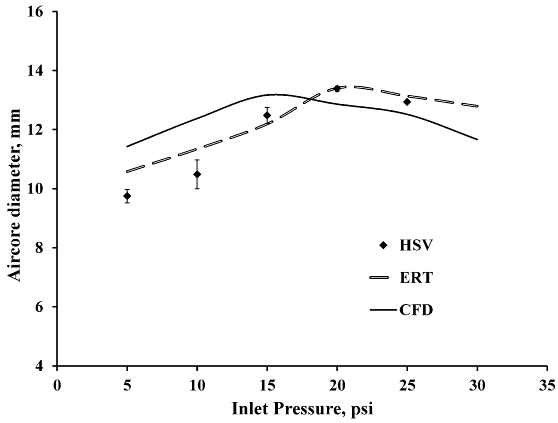



**Figure 3:** Variation of volumetric flowrate ($m^3$/hr) and underflow solids concentration with an increase in the spigot diameter at 15 psi pressure




(a)




(b)

**Figure 4:** Comparison of predicted (a) water split, (b) air-core diameter with experimental measurements for various inlet pressures in the 75 mm conventional Hydrocyclone with 15 mm spigot.

Cut size is under predicted and sharpness of separation is over predicted. Standard ASM model predictions are over predicted the fine particle size recovery. But the sharpness of separation is almost similar compared to the experimental values. Under prediction of rheology and absence of suitable drag force is the reason for the deviation of cut size and fine fraction recovery in case of DPM and Standard ASM model. Modified ASM model is able to predict the cut size and sharpness of separation accurately in comparison with experiments. Further, modified ASM model is used to run the multiphase simulations in 75 mm cyclone with various solids concentration (10-50% by weight).

The predictions of multiphase CFD model is validated with the classification curve of the 75 mm cyclone in Fig 6 (a), (b). An increase in the cut size is observed with the increment of feed solids concentration (Aurelien. et al., 2012).

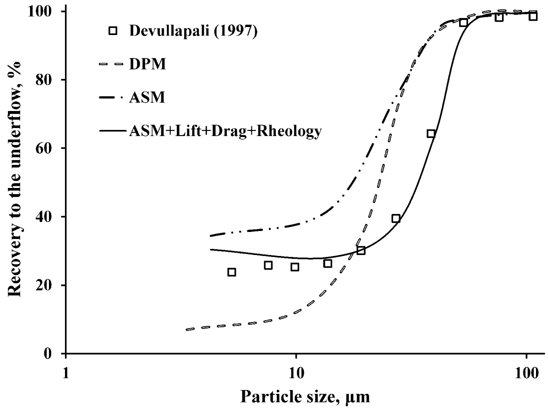
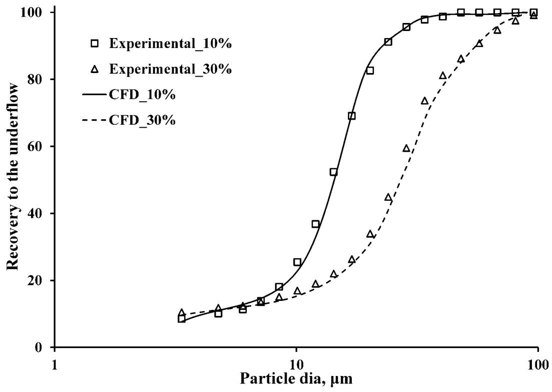
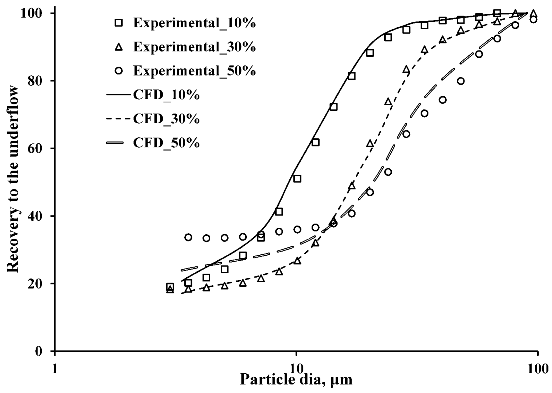



**Figure 5:** Experimentally measured $d_{50}$ compared with the DPM, ASM and modified ASM models in 250 mm Krebs hydrocyclone for 27.2% feed solids concentration.




(a)




(b)

**Figure 6:** CFD predicted $d_{50}$ compared with experiments in 75 mm cyclone for (a) 10%, 30% solids concentration

with 15 mm spigot, (b) 10%, 30% and 50% solids concentration with 17.5 mm spigot.

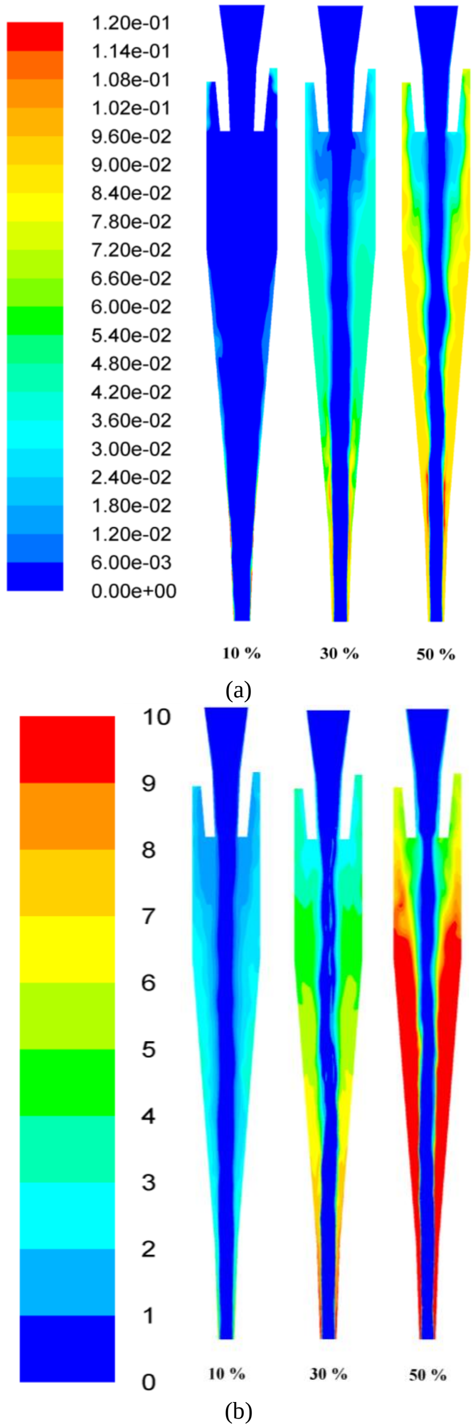



**Figure 7:** (a) Steady state volume fraction contours of 19.37 μm for various solid concentrations, (b) Steady state viscosity contours (in cP) for various solid concentrations in 75 mm cyclone.

The predicted particle classification curves for 10%, 30% solids by weight closely match with the experimental data with both spigot diameters. Under prediction of cut size and sharpness of separation is observed at high solids concentration (50% solids by weight). The reason may be the lack of turbulent dispersion forces and additional drag modification at high percent of solids. The effect of these forces will be addressed in the future work. Sharpness of separation decreased with an increase in the solids content. Cut size is decreased with an increase in the spigot diameter for 10% and 30% weight. More amounts of solids are going to underflow and a decrease in the cut size is observed.

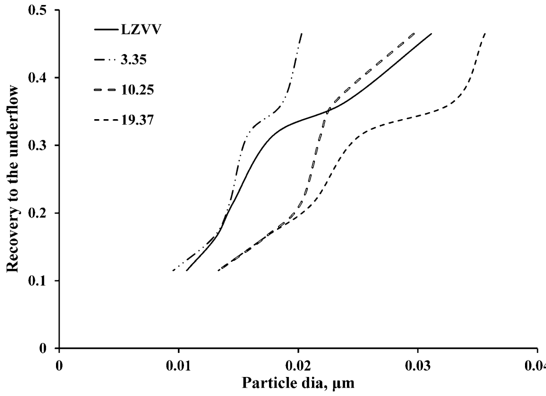



**Figure 8:** Particle equilibrium radius of different size particles compared to LZVV in 75 mm cyclone with 17.5 mm spigot for 10% solids concentration.

Figure7 (a) displays the steady state volume fraction contours of 19.37 μm for various solids content. In 10% solids concentration case, the cut size of cyclone (~12 μm) is lower than 19.37 μm particle size. Therefore, all the particles are going to the underflow. In 30% case cut size (~21 μm) is near to the 19.37 μm size. Hence, more than 50% particles are moving towards the underflow and reverse flow can also observed i.e. particles tries to escape through the overflow. In 50% case, the cut size (~ 35 μm) is much higher than the 19.37 μm particle. Hence higher percentage of solids is moving towards the overflow. Figure 7 (b) displays the viscosity contours 10%, 30%, and 50% solids concentration. An increase in the viscosity is observed with an increase in the solids content. Usage of Newtonian viscosity model corrected with fines able to show increased viscosity levels. High viscosities are observed in conical section compared to cylindrical section as the solids content is high in conical section. Figure 8 displays the mean radial position of the presence of maximum volume fraction of the particles in 75 mm hydrocyclone. In other words, this graph displays the particle equilibrium radius which means that, after the entrance of the particle in to the cyclone it reaches an orbit of certain radius based on particle size and tend to rotate in that particle orbit until its exit from the cyclone. In general finer particles have an equilibrium radius lower than LZVV and passes through over flow. Coarser particles have an equilibrium radius greater than LZVV and passes through underflow. Near cut size particles usually have an equilibrium radius equal to LZVV and have equal chances to pass through overflow and underflow. From the Figure 8 it can be observed that fine particles (3.35 microns) have an equilibrium radius less than LZVV, coarse particles (19 microns) have an equilibrium radius greater than LZVV and near cut size particles (10.25 microns) are showing an equilibrium radius equal to LZVV.

## CONCLUSION

Experiments are performed in 75 mm hydrocyclone for various solids concentration. Volumetric flow rate, water split, solid split, underflow solids percentage variation with respect to solids content is shown. Two-phase CFD model (VOF coupled with LES) is able to predict accurate water split and air-core diameter in comparison with ERT and HSV measurements. Multiphase CFD model with lift, drag and rheology modifications is able to predict cut size and sharpness of separation accurately up to 30% feed solids content. Deviations are observed at 50% solids concentration. Viscosity variation with feed solids content is displayed and Newtonian model corrected with fines able to predict the viscosity up to 30 cp. Equilibrium radius of 3 different size particles compared to LZVV is displayed. Modified ASM model with drag, lift and rheological corrections predictions are close to the experimental cut size and sharpness of separation with Devulapalli (1997) literature data.

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