SIMULATING MULTI-COMPONENT PARTICLES BEHAVIOUR DURING THE CLASSIFICATION PROCESS IN A HYDROCYCLONE USING MULTIPHASE CFD MODEL

Conference Paper · December 2015

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SIMULATING MULTI-COMPONENT PARTICLES BEHAVIOUR DURING THE CLASSIFICATION PROCESS IN A HYDROCYCLONE USING MULTIPHASE CFD MODEL

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ABSTRACT

Numerical simulation of the hydrocyclone is known for its complexity and non-trivial solving strategies. The flow inside the hydrocyclone is highly turbulent and intricate in nature. Most of the mathematical model reflects the single average mineral density for the hydrocyclone multiphase classification performance. The behaviour of multi-component particles in a hydrocyclone is superficially understood and the component interactions are unaccounted for most of the available mathematical models .In this work, multi size and density simulation of hydrocyclone are carried out using CFD approach. The turbulence is solved using the large eddy simulation (LES) model. The multiphase is modelled using the volume of fluid (VOF) and algebraic slip mixture (ASM) model. The multi-phase numerical simulation contains 10 phases at an instant i.e. water, air, 4 phases of magnetite and silica each, having different sizes and volume fractions. The mixture of magnetite and silica ratios i.e. 1:9, 2:8, 1:1 is considered for the understanding of interaction between components and sizes in complex flow system at optimized hydrocyclone conditions. The CFD model is able to predict the salient features of the cyclone flow fields in great detail, thus providing a better understanding of the solid recovery to the underflow, where authors have observed high R_s for the heavier particle i.e. magnetite. Separation characteristics of the silica and magnetite particles are explained using locus of zero vertical velocities (LZVV) and equilibrium radius.

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

NOMENCLATURE

a characteristic length
p pressure
u velocity
ρ density
μ dynamic viscosity
v_q Velocity of phase q.
a_q Volume fraction of qth phase
k Turbulent kinetic energy
ε Turbulent dissipation rate
μ_t Turbulent viscosity coefficient.

BACKGROUND

Hydrocyclone is a static device that applies centrifugal force to a liquid mixture to promote the separation of heavy and light components. Because of its static operation, and high energy efficiency, it is vastly used in many industries like Mineral, chemical, pharmaceutical etc for classification purpose. The naturally occurring mineral ores include two and more components in it to get separated. During the grinding and separation processes these material interferes with each other due to encompassing different sizes and density at the same time and reduces the efficiency. Hence it is very important to study the multicomponent effect including the complex flow pattern inside the hydrocyclone. Various experimental studies with a limited data have shown the effects of the single average density on the particle flow behaviour. Mainza (2006) studied the classification behaviour of UG2 platinum ore in hydrocyclones. During the classification, the coarse silicates report to the overflow and the fine chromites to the underflow. The shape of efficiency-curve for overall classification of solids was observed different than normal. The classification curves for high density component (Chromite) and low density component (Silica) oriented at very fine solids and very coarse solids respectively. They observed that Individual density component follow standard shape for efficiency curves with low density component displaying fish-hook nature. So they realized that the classification can be modelled by considering individual density fractions. Weller et al., (1988), tried to develop a multi-component model for grinding and classification circuits. They used copper ore including copper, pyrite and gangue for their study. Kawatra, (2006) tried to address the inflections in hydrocyclone efficiency curves using mixture of quartz and magnetite. Narasimha et al., (2012) attempted to develop single component model with average density. This model included additional term, a density function, which was flexible enough to extend that to multicomponent classification model. Narasimha et al., (2014), recently proposed a model including the effect to individual particle density and its effect on the mixture flow in classification phenomenon.

Computational Fluid Dynamics (CFD) is proven as an efficient tool to study the effect of design variables on the hydrocyclone classification performance. Usage of suitable turbulence model is the key for accurate flow field predictions of any hydrocyclone. Usage of κ-ε and Re-Normalization group (RNG) κ-ε turbulence models were limited due to isotropic turbulence assumption i.e. equality of Reynolds stresses in all directions, prediction of high turbulence viscosities and unrealistic tangential velocities Hsieh and Rajamani, 1988; Narasimha et al., (2005). Even though Reynolds Stress Model (RSM) doesn't model the turbulence accurately with the equilibrium turbulence assumption in particular to sub grid scale modelling, it was able to predict reasonable velocity profiles with low computation power. Successful implementation of RSM model in the tangential and axial velocity predictions can be seen in recent literature [Brennan et al., (2007); Delgadillo and Rajamani, (2005); Slack et al., (2000); Vakamalla and Mangadoddy, (2015); Wang et al., (2007)]. By solving the large scale eddies and modelling small scale eddies one can capture time dependent vortex oscillations, non-equilibrium turbulence Nowakowski et al., (2004). LES was already proved as better turbulence model in terms of accurate flow field predictions [Brennan, (2006); Narasimha et al., (2006b); Vakamalla et al., (2014)]. Therefore, present paper used LES to model the turbulence. Algebraic Slip Mixture (ASM) model was used by various researchers to study the multi-phase flow behaviour in hydrocyclones [Chu et al.,(2012); Narasimha et al., (2012a); Narasimha et al., (2006a)]. Very limited studies were available on the full Eulerian-Eulerian multi-phase model usage for performance predictions Raziyeh and Ataallah,(2014) because of its high computation usage as it solves individual equations for continuity and momentum for each phase.

Experimental evidences of influence of multicomponent particles on hydrocyclone efficiency curve have motivated the researchers to conceptualize the modelling of hydrocyclone performance based on multicomponent behaviour. The interaction of the particles can be very well estimated by the computational fluid dynamics. In this paper, the CFD simulations of hydrocyclone have been pursed to understand the multi-component behaviour using the multiphase model having water, air, particles of different sizes and densities as different phases. With a main purpose of understanding the phenomena of interference between two different components by varying the proportion of mixture feed (silica: magnetite) with respect to the pure component case.

MODEL DESCRIPTION

The CFD approach used here is same as that used by Narasimha et al. (2012a) and Vakamalla et al. (2014). Unsteady equations of motion for a mixture are solved by LES turbulence model.

Turbulence modelling

For solving the high swirling flow produced inside hydrocyclone LES turbulence model was used.

LES model

Unsteady equations of motion for a slurry mixture are solved by using Large Eddy Simulation.

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

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

Here u_{mi} is the i[th] component of slurry velocity vector. Sub grid scale stresses $\tau_{t,ij}$ are solved with the Smagorinsky (1963) SGS model. Drift tensor $\tau_{d,ij}$ which arises from the derivation of Mixture model accounts for the transport of momentum as a result of segregation of the dispersed phases.

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

Multiphase modelling

VOF model

VOF model is a numerical technique used for tracking the interface between free surfaces by solving the continuity equation (9). An additional equation (5) for the volume fraction of the air α is solved and this tracks the position of the air-core in this problem.

$$\frac{\partial \alpha_q}{\partial t} + u_i \frac{\partial \alpha_q}{\partial x_i} = 0 \qquad (4)$$

$$\sum_{q=1}^{n} \alpha_q = 1 \qquad (5)$$

Algebraic Slip Mixture model

When the multicomponent particles having different particle size distribution (PSD), then the mixture model could be adopted for various phases consisting different sizes and densities. For the know density and different PSD considering four sizes the simulation have been done as shown in Table 1. This is a simplified version of VOF which solves the equations of motion for the fluid mixture and transport equations for the volume fractions of any additional dispersed phases

$$\frac{\partial \alpha_k}{\partial t} + \Delta.\alpha_k u_m + \Delta.\alpha_k u_{km} = 0 \qquad (6)$$

$$u_{km} = u_k - u_m \qquad (7)$$

The u_{km} is the drift velocity of the phase k with respect to the mixture and is calculated from the slip velocities of the other dispersed phases:

$$u_{km} = u_{kc} - \sum_{i=1}^{n} \frac{\alpha_k \rho_k}{\rho_m} u_{lc} \qquad (8)$$

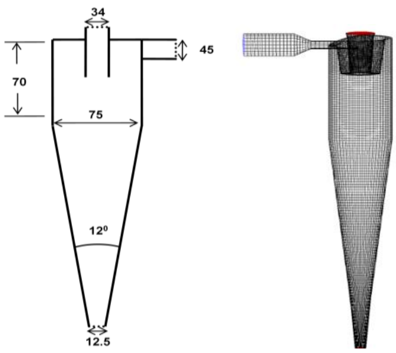
u_{kc} is the slip velocity of the dispersed phase k relative to the continuous fluid phase c and is calculated from the equilibrium drag assumption assuming as quasi equilibrium state at the interface of two phases. Manninen (1996) This means that the particles which makes up phase k, changes rapidly in presence of the mixture fluid medium, hence it is always considered to be at terminal velocity relatively.

SIMULATION

The equations were solved using the unsteady segregated solver with a time step of 5x10^{-5}s. The geometry and the mesh of 3 inch hydrocyclone was created using ICEM is shown as Figure 1(a) and 1(b). SIMPLE is used for pressure velocity coupling, PRESTO for pressure and QUICK for the VOF equation, solving the water- air phase initially. The momentum equations used QUICK with the Bounded Central Differencing with LES. The numerical approach was to start with the cyclone domain "full of water" and at a fixed inlet flow rate and integrate in time until the swirl created a axial region of negative pressure forming the air-core. At this point the backflow volume fraction of air at the overflow and underflow was set to 1 and the simulation proceeded so that air was drawn in, to form the air core, and then conducted till steady mass flow rates out the overflow and underflow and a steady feed pressure were obtained.

Table 1: Details of inlet phases

Phases	Density Kg/m^3	Size (microns)
Water	1000	-
Air	1.27	-
Silica (4 no.)	2650	2.75, 11, 22, 52.32
Magnetite (4 no.)	4900	2.75, 11, 22, 52.32



(a) (b)

Figure 1: (a) Geometry and (b) mesh of 3 inch hydrocyclone.The multiphase simulation were run using mixture Model(ASM), having 10 phases i.e. water, air, 4 sizes of silica and 4 sizes of magnetite as shown in Table 1.

Particles shown in Table 1 were fed from inlet with different volume fractions making a total of 10% solids in feed slurry in each of the case having, 3 proportions 1:1, 2:8 and 1:9 (Magnetite : Silica) .The size distribution of raw silica and magnetite are shown in figure 2.

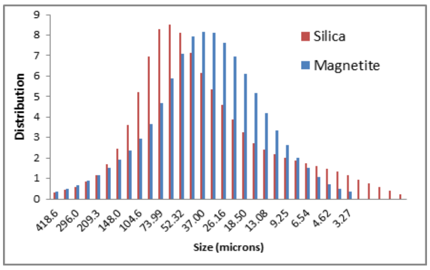


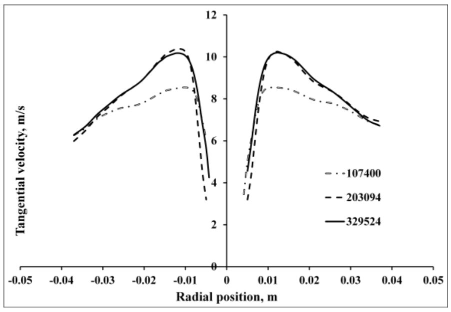
Figure 2: Silica and Magnetite size distribution

RESULTS & DISCUSSION

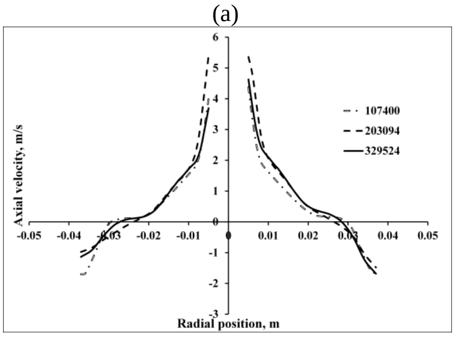
Three different meshes of 107K, 203K and 329K are used for grid independence check. The grid check data with respect to tangential and axial velocities is shown in Figure 3. It is observed that tangential velocities, axial velocities predicted by 203,094 nodes are very close to 329,524 nodes. Therefore, simulations are further continued with 203,094 nodes. The initial simulations were run for water-air system to validate the model used, comparing it with the available water data sets and followed by 10 phase simulations was conducted. The impact of various sizes and density on flow field and separation performance has been observed and discussed.

Flow split Vs Pressure

The water based simulation and experimental data's of water split (R_f) are found in close agreement. With the increase in the pressure at inlet, the water split is proportionally decreases. An increase in the pressure simultaneously increases the centrifugal forces, which directly has an effect on air core diameter. An increase in the air core diameter shown in Figure 5 decreases the flow split to the underflow. The two-phase CFD simulation studies are validated against the Electrical Resistance tomography (ERT) data, and the high speed video image analysis data. ITOMS ERT acrylic conical section with 16 electrodes around the periphery is used for the measurements of two-phase concentrations. Thus estimating the air core profiles using the ERT data are well established Rakesh et al. (2014). A good agreement is found between CFD, ERT and High speed video imaging technique. Various analysis with multicomponent are discussed further in details to understand the interactions among particles.



(a)



(b)

Figure 3: Prediction of (a) tangential and (b) axial velocities by different mesh sizes at 0.2m from top of the cyclone.

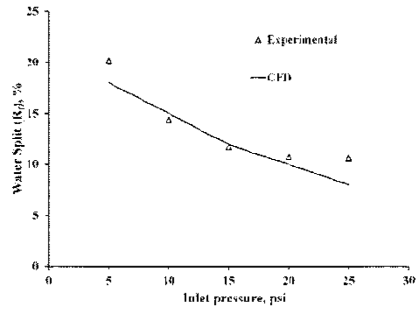


Figure 4: Water split comparison – experimental vs CFD simulation.

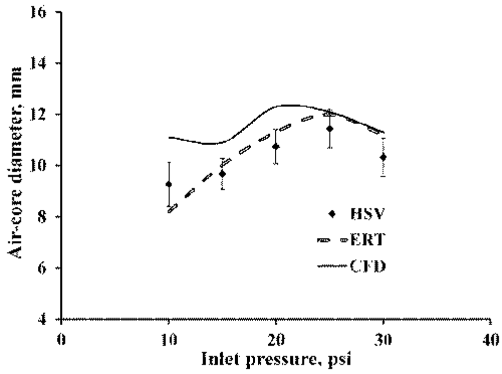


Figure 5: Cross validation of CFD predicted air core diameter with HSV and ERT for 12.5 mm spigot.

A. Comparison of volume fraction distribution of silica and magnetite of same size

In the simulation the bi-component mixture was fed as a feed to hydrocyclone as given in Table 1, the heavier is expected to reach a higher tangential velocity earlier than the lighter one because of it high mass. Therefore, higher density particles are expected towards the wall. Figure 6 displays the comparison of instantaneous volume fraction contours of silica and magnetite for different size particles.

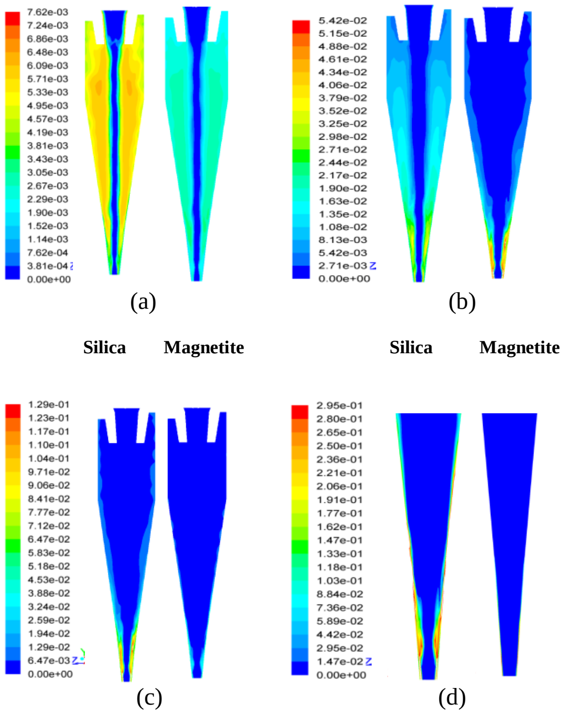


Figure 6: Silica (left) and Magnetite (right) volume fraction contours of (a) 2.75 micron, (b) 11 micron, (c) 22 micron and (d) only spigot region - 52.32 micron (From a mixture of 1:1- silica and magnetite) particles.

From the contours, it is observed that magnetite phase is moving faster and occupying the wall side with higher tangential velocity, the silica phase is still found to be dispersed inside the flow region as expected. In the Figure 6 (a), Silica and magnetite being at very small size (2.75 microns), the dispersion is observed for both cases. Figure 6 (b) illustrates the heavier, magnetite occupying the major fraction in wall side; whereas the silica of same size is dispersed in the fluid regime. With the increase in size of the component it is observed that magnetite reports to the underflow higher as compared to the silica. As seen in figure 6(c) and 6(d) compared to silica, the maximum percent of magnetite has reported to underflow at the same moment, where in figure 6(d) the contour is shown at lower conical area.

B. LZVV - locus of zero vertical velocity

Locus of zero vertical velocity (LZVV) is an imaginary line inside the turbulent flow of hydrocyclone where the vertical velocity appears to be zero. According to the equilibrium orbit theory, Kelsell (1952), the particle reporting outside LZVV goes to underflow and the inside one reports to the overflow stream. In Figure 7, pure silica, pure magnetite and mixtures having 50% and 90% silica composition, the LZVV positions are compared. It is observed that only magnetite LZVV lays out most towards the wall and with the decrease in magnetite % the LZVV shifts towards the air-core.

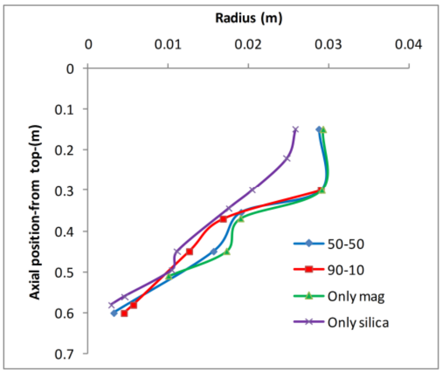


Figure 7: LZVV of various proportions of magnetite

C. Tangential velocity plots

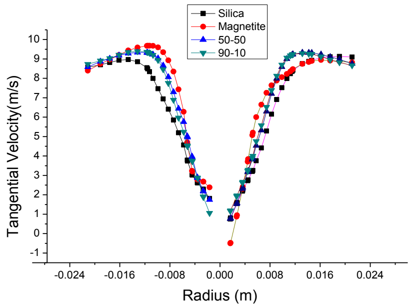


Figure 8: CFD Predicted mean tangential velocities at 300 mm from top of the hydrocyclone (near the cylindrical and conical junction) for different proportions of magnetite and silica.

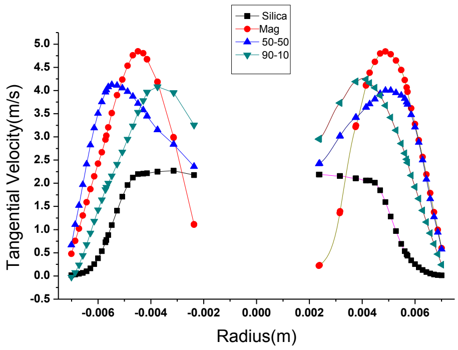


Figure 9: CFD Predicted mean tangential velocities at 600 mm from top of the hydrocyclone (near spigot) for different proportions of magnetite and silica.

Figure 8 and 9 shows the tangential velocities at a height of 300 mm, which is near the intersection of conical and cylindrical portion. The tangential velocities of magnetite in 100% magnetite slurry is found higher than that in the mixtures i.e. 1:1 and 8:2 proportions. When it leads to the lower, conical portion (Figure 9) the magnetite tends to move down fast, pushing the silica towards air core, forming flow reversal and the particles move to the overflow. The tangential velocities of particles are observed significantly different at various proportions i.e. with increase in the interference the characterisation and

PSD of the particle reporting to the outflows changes which is further described in results and discussions.

D. Comparison of vectors – silica at 52.32 micron size at underflow

In lower conical section the converged area intensifies the flow pattern and the flow behaviour changes. Figure 10 displays the predicted vectors of (a) silica 1:9 magnetite mixture of 52.32 microns and (b) pure silica case of 52.32 microns in the conical section. It is observed that when magnetite is present in mixture it tries to occupy the wall side and pushing the silica particles inwards to the flow, this causes the high reversal flow for the silica particles, as a result of which the d_{50} of silica increases in mixtures as compared to the pure silica case which we have also seen in the LZVV shifting case.

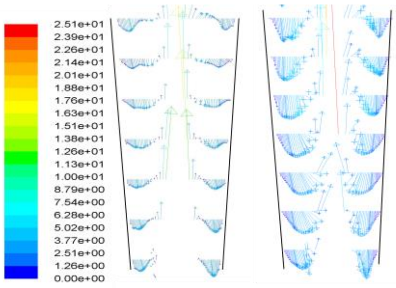
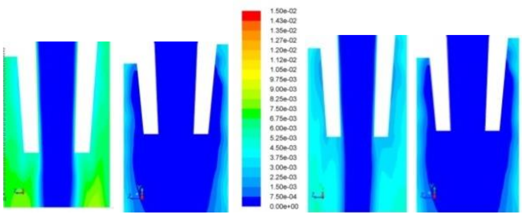


Figure 10: Contours for comparision of 52.32 micron size silica in underflow area (a) silica from 1:9 mixture and (b) Pure silica

E. Contours at vortex finder

Vortex finder is a position where due to the divider wall the velocity suddenly decreases, leading to a phenomenon called short-circuiting. As discussed in previous section the interference of magnetite in a mixture with the silica is also observed near the vortex finder. The plot shows the comparison between 9.25 micron particle of (a) silica in 50-50 mixture (b) magnetite in 50-50 mixture (c) pure silica and (d) pure magnetite .Where the finer silica gets short circuited easily in a mixture feed rather than in pure case, while magnetite attaining easily the similar pattern in mixture and pure form at sizes near by the d_{50}. The dispersion of silica is found to be higher with high residence time in the magnetite and silica mixture. In pure silica case, since having only one component, the separation takes place based on the size i.e. the larger reports to the underflow & lighter to overflow.

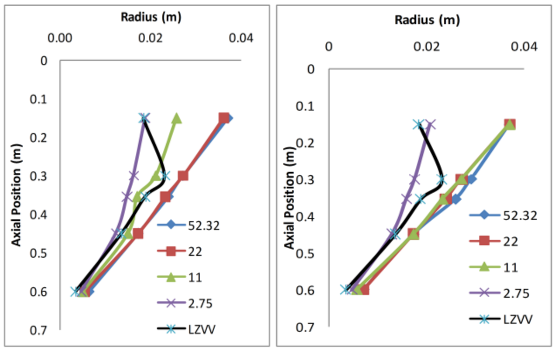


(a) (b) (c) (d)

Figure 11: Comparison of magnetite and silica distribution at vortex finder area (a), (b) in 50% and (c) pure silica (d) pure magnetite

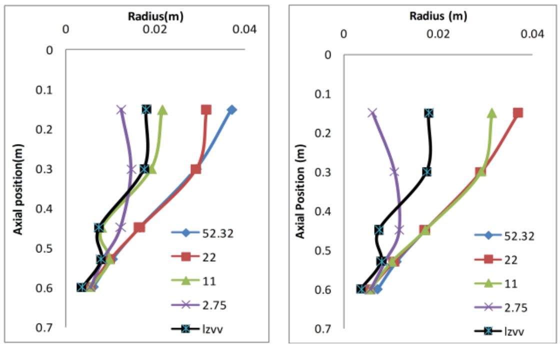
F. Mean position of Maximum Volume fraction

Mean position of the volume fraction spread is found by plotting positions of maximum volume fraction of particles inside hydrocyclone radially along the LZVV and which gives an idea for the separation line of particle moving to underflow and overflow. In Figure 12 the maximum volume fraction's mean position is tracked. This is then compared to the LZVV to know the place of the particle where it lies, by which the directions of the flow could be estimated. It is observed that the silica of 11 micron reports to overflow but magnetite, 11 micron is reporting to underflow showing the different performances of components in same flow fields.



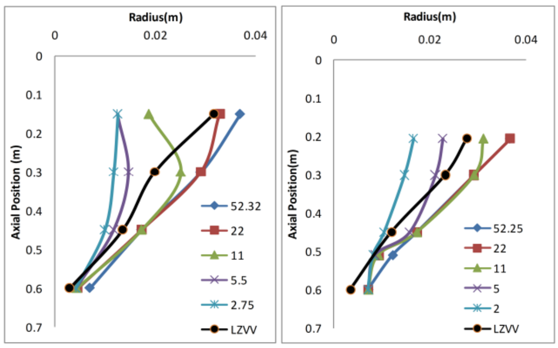
(a) (b)

Figure 12: Mean position of volume spread (a) silica and (b) magnetite in 1:1 proportion



(a) (b)

Figure 13 : Mean position of volume spread (a)silica and (b)magnetite in 8:2 proportion



(a) (b)

Figure 14: Mean position of volume fraction spread (a) pure silica and (b) pure magnetite

The obvious reason for the occurrence is the mass and density difference. Further comparisons have made among

100% single density particle slurry simulation and particles in a mixture having silica as a proportion (1:1 and 8:2), the interaction are as shown in figure 13 & 14. Comparing Figure 13 and Figure 14, we can see the difference in the interaction of two components at different proportional inputs. In case of 1:1 proportion silica 11 is nearly escaping from the reversal flow, where as in the 8:2 proportion having silica as major portion 11 micron particle directing to the overflow. At the same instant the 100%silica slurry's cut size has increased and lies between 11 to 22 microns (nearby 11 microns), which is also seen in experimental cases. Similarly the magnetite behaviour also changes with respect to pure and varying proportions in seen in (b) part of Figure 12, 13 and 14.

CONCLUSION

Multi size and density simulations are carried out in 3 inch hydrocyclone using LES turbulence model and ASM multi-phase model with a input of 1.01 m/s feed velocity at 103.5 Kpa pressure. Through the CFD study's authors have observed that the heavier particle having higher mass, acquires high centrifugal force and inhabits the wall portion mostly. At times when we increase the percentage of magnetite, the silica (lighter particle) gets pushed up through high reversal flow, which changes the cut-size as well as the solids recovery in the phenomenon. Using CFD simulations of pure component and components at different proportion, LZVV have given an idea that with higher % of magnetite shifts more towards wall, increasing the cut-size. The mean position of maximum volume fraction spread studies shows the changing cut-size of silica and magnetite with the change in the component proportions in feed mixture. The analysis of simulations could compared with the experimental data's in future including multicomponent and turbulent conditions for the better understanding of hydrocyclone behaviour with naturally occurring ores.

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