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Rheology based CFD modeling of magnetite medium segregation in a dense medium cyclone

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Abstract
In this work, an improved multiphase computational fluid dynamics (CFD) model is developed for simulating medium segregation in a dense medium cyclone. This model approach uses the modified Mixture model with the granular option and Reynolds stress model (RSM) to resolve the turbulent mixing of the particles. Rheological behavior of the medium is considered through various forms of viscosity models such as granular viscosity, Newtonian and non-Newtonian model corrected with particle loading and fraction of ultra-fines. Multiphase simulations using the granular viscosity option although predict the overall slurry volume split, product medium densities better than Newtonian models, but the mixture viscosity values are restricted to substantially lower values close to water viscosity levels. Simulations using the Newtonian viscosity model corrected with particle loading and fine fraction below 53µm size are predicted the overall medium viscosity levels well above water viscosity levels, but under predicted the cyclone underflow medium density to the experimental data. Multiphase simulations with the Non-Newtonian Herschel-Bulkley viscosity model is able to predict the medium segregation close to the gamma ray tomography data and the predicted medium viscosity levels are increased up to 18 cp. Overall predicted product medium densities, underflow volume split and radial medium segregation levels are compared to the experimental data. Lagrangian particle tracking (LPT) is super imposed on converged medium simulations used for coal partitioning predictions. This model can be further used in developing new designs in the future.

Key words: Slurry Rheology, dense medium cyclone, computational fluid dynamics, medium segregation, multiphase flow

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1. Introduction

Dense medium cyclones (DMC) are widely used operating devices for the separation of clean coal from ash content material in coal preparation plants and other heavy medium separations in diamond and iron ore industries. These devices are having potential for high throughputs and sharp separations. The usual coal particle size range involves 0.5–50 mm (+ 10% near gravity material). Operating principle of DMC has been well explained in the literature [1]. DMC separates the coal particles on basis of density difference under the influence of centrifugal forces. Medium with coal particles fed tangentially through the cyclone inlet where the centrifugal forces are produced due to which the heavier density ash particles moves towards the wall and passes through underflow as reject. Lower density coal particles moves along the forced vortex and passes through overflow due to drag dominance.

Magnetite suspension used in DMCs behaves as a non-Newtonian fluid [2]. The adoption of Newtonian viscosity model formulation for magnetite suspension is not a valid option while developing an accurate mathematical model of DMC performance. Separation efficiency of the coal particles depends on rheological properties of the magnetite media. Rheological properties are controlled by medium particle size, shape and density [3]. The effect of rheology is more significant on fine particles than the coarser particles [4]. Even with very fine particles at low concentrations, the suspension shows unstable behavior. Therefore this complex rheological behavior cannot be modeled simply by single rheological parameter. Till date the adopted computational fluid dynamics (CFD) models for DMC mainly utilized the magnetite slurry rheological model based on total solids volume fraction correction to Newtonian behavior. Consideration of the effect of fine fraction especially below 53 micron size of the medium particles and the influence of shear rate on the viscosity of magnetite suspension were not implemented in previous CFD modeling studies of DMCs. A brief review of previous work in the light of these issues in DMCs is presented in the following section.

1.1 Brief literature review

Flow in DMC is multiphase in nature as it consists of water, air, magnetite, coal of different particle sizes and densities. In addition to this flow is turbulent. Therefore precise experimental measurements of velocity and air-core are difficult and very sparse literature is available till date. Galvin
and Smitham [5] used X-ray tomography; Subramanian used Gamma ray tomography (GRT) [6] to measure the density distribution inside the cyclone. Modeling is a better option and earlier modeling studies involve the development of designs based on empirical, semi empirical and analytical methods [7-9] with limited test data. But the reliability of these models is very low with respect to change in design parameters. Numerical modeling which involves solving of fundamental governing equations of fluid flow is recognized as the best approach for understanding of separation mechanism inside the industrial cyclones.

The first numerical model on DMC was developed by Zughbi et al. [10] considering a 2-D axis symmetry model with an imposed air-core. Anisotropic turbulence was modeled by modified Prandtl mixing length model [11, 12]. The reported results were associated with unrealistic tangential velocities. Suasnabar and Fletcher et al. [13] studied the flow in a 200mm DMC by assuming air fluid interface as a slip wall and turbulence was modeled by using κ-ε, modified κ-ε, Reynolds stress model (RSM) model [14]. The data with RSM turbulence model compares well with Wood [9] coal partitioned experimental results. Successful implementation of RSM for the accurate predictions of flow field in various designs can be observed in the recent works [15-21]. In the studies of Narasimha et al. [15-17], turbulence was modeled using DRSM and Large eddy simulation (LES) models for the medium segregation in a 350mm DMC. The authors compared velocity predictions with differential Reynolds stress model (DRSM) and concluded LES model has the credibility in accurate prediction of velocities. Even though LES needs finer grid, more computation time, it can give precise air-core position [22, 23].

The flow in cyclones involves multiphase such as air, water, magnetite and coal. Therefore, there is a need of multiphase model for efficient computational modeling. There are number of multiphase models available in CFD for simulating such a complex multiphase turbulent system. These include the full Eulerian multiphase approach, the simplified Eulerian approaches such as volume of fluid (VOF) and Algebraic slip mixture model (ASM) and the Lagrangian approach. In full Eulerian multiphase flow approach, where a set of continuity, momentum and turbulence equations is solved for each phase has been used for systems with very high dispersed phase concentrations, where solid/solid interactions carry a significant amount of the stress. The disadvantage of the full Eulerian multiphase modeling approach
has been its high computational cost. Further implementations in commercial CFD codes have until recently been limited to adopt the k-epsilon/RSM models for turbulence. VOF [24] and ASM [25] are the simplified multiphase models solved for the equations of continuity, momentum and energy of mixture. Additional equations are solved for volume fractions of additional phases. Simplified multiphase models are better than the full multiphase models in terms of uncertainties in closure relations and computation timing [25]. VOF with RSM turbulence model gives accurate predictions with respect to flow field and air-core were the basic steps for the evolution of multiphase modeling [13, 26]. Brennan et al. [27] used ASM to model the dispersed phase and the air-core in 350mm DMC. The authors have observed reasonable medium density profiles but the segregation levels were far from the experimental results of Subramanian et al. [6]. Later Narasimha et al. [15-17] modified the ASM model by adding the shear lift forces, Newtonian viscosity correction and reported the improved results. But the segregation levels were still over predicted near the wall compared to the experimental Gamma ray tomography data. ASM model was also successfully used to model the multiphase flows in DMC’s of by other researchers [18-20]. The flow of coal particles were modeled by Lagrangian particle tracking (LPT) method [16, 18, 19]. Even though LPT can show diverse behavior of particles of different sizes and densities it cannot be used for concentrated slurries as it was tracking dilute particle motion. LPT model doesn’t consider the particle-particle interactions, particle concentrations effect on the flow medium at high concentrated slurries [28, 29].

This problem can be solved by CFD-DEM coupling method. The conventional CFD method was used typically for modeling the air-core and the flow of magnetite medium of DMCs [15-17, 27]. Discrete element method (DEM) was used to model the flow of coal particles in DMCs [30, 31]. The DEM technique is having an advantage over the regular LPT model as it can model the particle-particle interactions by applying Newton’s laws of motion to individual particles. Chu et al. [31] attempted one way CFD-DEM coupling studies for DMC and explained the effect of medium: coal ratio and the importance of pressure gradient force on the cyclone separation. One way coupling was similar to LPT; it doesn’t consider the particle-particle interactions on medium flow. To overcome these Chu et al. [30] considered a group of real particles as a single parcel particle and the simulated results of coal partition performance and medium density differential were compared with experiments. The shortcoming of this approach was
the assumption of properties of parcel particles as it cannot represent the exact behavior of group of real individual particles under the same operating conditions. In their latest studies [18] they assumed mono sized spherical particles to rule out the concept of parcel particle. But particle size and shape plays an important role in the separation. In spite of DEM’s ability to consider the particle-particle interactions, particle concentration effect on the fluid medium it has certain limitations also. As the size of coal particles involves significant fraction of fines (below 3 mm size) one need to apply this model for billions of particles which is computationally very expensive. The assumptions used in coupling may simplify the problem but the complete research yet to be carried out in realistic conditions.

He and Laskowski [4] modeled the magnetite suspension rheology with Bingham, Casson and Herschel-Bulkley viscosity models and found experimental flow behavior can be described by Casson viscosity model very well. Suasnabar et al. [32] studied the effect of non-Newtonian rheology of the medium with two different models (Hershey Bulkley, Power law) along with and without turbulence phenomena on a two-dimensional 200mm DMC and found the influence of turbulence was more significant on the medium than the rheology. Narasimha et al. [15-17, 33] used the modified rheological model of Ishii and Mishima [34] to study the performance of DMC and obtained improved solids slurry concentration, density results near the wall with comparison of Gamma Ray Tomography data of Subramanian et al. [6]. Wang et al. [19, 20], Chu et al. [18] also used the similar model with a scale factor to account the rheological effects.

1.2 Present work

Present paper aims to develop an improved CFD model for predicting the medium segregation in a 350 mm DMC. The contribution mainly include on implementation and testing of different rheological models such as Granular viscosity, Newtonian and non-Newtonian model formulations corrected with total solids loadings and fraction of fines factors through CFD model for simulating magnetite segregation at moderate feed solids concentration. This CFD model includes additional shear lift force which is important at higher concentrations near the cyclone wall. The results are compared with the gamma ray tomography data, measured in a 350 mm DSM cyclone operating only with the magnetite medium. The predicted viscosity levels of medium inside the DMC are compared among the various rheological
formulations based CFD models and assessed the suitability of rheological models on the prediction of magnetite medium segregation levels. Finally coal partitioning performance is simulated using LPT model on top of the medium segregation simulations.

2. Model equations

2.1. Turbulence Modeling

The CFD approach used here is same as that used by Brennan et al. [35], Narasimha et al. [36].

Unsteady transport equations given below are solved for individual Reynolds stresses $\bar{u}_i'\bar{u}_j'$ [14].

$$\frac{\partial}{\partial t} \left( \rho \bar{u}_i' \bar{u}_j' \right) + \frac{\partial}{\partial x_k} \left( u_k \rho \bar{u}_i' \bar{u}_j' \right) = \phi_{ij} + P_{ij} + D_{T,ij} + D_{L,ij} - \epsilon_{ij} + F_{ij}$$  \hspace{1cm} (1)

Here $\phi_{ij}$ is pressure strain, $P_{ij}$ is stress production, $D_{T,ij}$ is turbulent diffusion, $D_{L,ij}$ is molecular diffusion, $\epsilon_{ij}$ is dissipation, $F_{ij}$ is production by system rotation is modeled by the following to close the equations.

$$\phi_{ij} = -(C_1 \rho \varepsilon + C_1' p) b_{ij} + C_2 \rho \varepsilon \left( b_{ik} b_{kj} - \frac{1}{3} b_{mm} b_{mm} \delta_{ij} \right) + \left( C_3 - C_3' \sqrt{b_{ij} b_{ij}} \right) \rho k S_{ij} +$$

$$+ C_4 \rho \kappa \left( b_{ik} S_{jk} + b_{jk} S_{ik} - \frac{2}{3} b_{mn} S_{mn} \delta_{ij} \right) + C_5 \rho \kappa \left( b_{ik} \Omega_{jk} + b_{jk} \Omega_{ik} \right)$$

$$+ b_{ij} \frac{\partial}{\partial x_k} \left( \frac{\partial u_i'}{\partial x_k} + \frac{\partial u_j'}{\partial x_k} \right) \frac{\partial u_i'}{\partial x_k}$$

$$D_{T,ij} = \frac{\partial}{\partial x_k} \left( \frac{\mu_i}{\sigma_k} \frac{\partial u_i'}{\partial x_k} \right) , \sigma_k = 0.82$$

$$D_{L,ij} = \frac{\partial}{\partial x_k} \left( \frac{\mu}{\sigma_k} \frac{\partial u_i'}{\partial x_k} \right) \epsilon_{ij} = \frac{2}{3} \delta_{ij} \rho \varepsilon$$  \hspace{1cm} (2)

Where $B_{ij}$ is Reynolds stress anisotropy tensor, $\Omega_{ij}$ is mean rate of rotation tensor, $S_{ij}$ is mean strain rate, $\mu_i$ is turbulent viscosity. Turbulent viscosity is computed from the kinetic energy and dissipation rate
transport equations as per κ-ε model and constants used in the quadratic pressure strain are $C_1 = 3.4$, $C_1^* = 1.8$, $C_2 = 4.2$, $C_3 = 0.8$, $C_3^* = 1.3$, $C_4 = 1.25$, $C_5 = 0.4$.

### 2.2 Multiphase modeling – Mixture model with lift forces and rheological models

In the ASM approach [25], mixture velocity is calculated by a single momentum equation; volume fraction of each phase is obtained by solving individual continuity equation. Continuous fluid phase is assumed as primary (represented by $c$); Particles are assumed as dispersed phase (represented by $p$).

\[
\frac{\partial}{\partial t} (\alpha_p u_i) + \frac{\partial}{\partial x_i} (\alpha_p u_{pm,i}) + \frac{\partial}{\partial x_i} (\alpha_p u_{pm,i}) = 0
\]

\[
u_{pm,i} = u_{pi} - u_i \tag{4}\]

Drift velocity of the mixture $u_{pm,i}$ which is due to centrifugal force is calculated from the slip velocity of dispersed particulate phase relative to the continuous water phase $u_{pc,i}$.

\[
u_{pmi} = u_{pci} - \sum_{j=1}^{n} \frac{\alpha_i \rho_i}{\rho_m} u_{ci} \tag{5}\]

\[
u_{pci} = u_{pi} - u_{ci}\]

The general slip velocity $u_{pc,i}$ which is used based on Manninen et al. [25] has been modified to incorporate (i) a shear dependent lift forces [37].

\[
u_{pci} = \frac{d^2 (\rho_p - \rho_m)}{18 f_{rep} \mu_c} \left[ \frac{g_i}{\mu_i} + \frac{\partial}{\partial x_j} u_{mi} - \frac{\partial}{\partial x_j} u_{mj} + 0.75 \frac{\rho_c}{\rho_p - \rho_m} C_{rep} \varepsilon g \omega_{my} u_{pc,i} \right] \tag{6}\]

The last acceleration term in the bracket is due to lift force. This equation is implemented in ANSYS’s Fluent by a custom slip velocity user defined function. Lift coefficient is modified as suggested by Mei [38] to apply it for high Reynolds number. The modeling of $f_{rep}$ is by using Schiller-Naumann drag law [39] with an additional correction factor by Richardson and Zaki [40] correlation to account hinder settling of the particles.
The slip velocity $u_{pmi} \text{ (m/s)}$ of the air phase is disabled and assumed to be zero. Here $\alpha_p$ is the volume fraction of particles, $C_{lp}$ is the lift coefficient, $f_{rep}$ is the drag coefficient, $d_p$ (m) is the diameter of the phase p, $g$ (m/s$^2$) is the component of gravity, $Re_p$ is the particulate Reynolds number, $\varepsilon$ is permutation tensor, $\omega$ is the vorticity of the mixture.

### 2.3 Rheology models

Rheology is one of the key factors to determine the medium segregation at high particle loading in DMCs. Therefore the work has been considered to study the medium segregation with different viscosity formulations including granular viscosity, Newtonian and non-Newtonian viscosity models as a function of particle concentration.

#### 2.3.1 Granular Viscosity model (GV)

As a base model, calculations are performed with basic granular viscosity (GV) formulation incorporated in Fluent which has been proposed by Ding and Gidaspow et al. [41, 42]. Granular shear viscosity arises from particle momentum exchange due to translation and collision is accounted by enabling the granular solid option. Details of granular viscosity formulation incorporated in Fluent manual [43] is as follows.

$$\mu_m = \mu_{p,\text{col}} + \mu_{p,\text{kin}}$$

In the experimental work of flow through annular shear shell; Bagnold [44] observed that in low shear region viscous forces dominates the flow and stresses are proportional to shear rate. On the other side in high shear region, grain inertia dominates the flow behavior and stresses are proportional to square of the shear rate and independent of fluid viscosity. Gidaspow [41] modeled the expressions for shear dependent granular viscosity as shown in equations 8.1-8.3 by following the above approach.

Collision or Bulk viscosity is modeled as

$$\mu_{p,\text{col}} = \frac{4}{5} \alpha_p^2 \rho_p d_p g_{\alpha,pp} \left(1 + e_{pp}\right) \left(\frac{\Theta_p}{\pi}\right)^{1/2}$$

(8.1)
Kinetic viscosity is modeled as

\[ \mu_{p,kin} = \frac{2\mu_{sat}}{96(1 + e_{pp})g_{o,pp}} \left[ 1 + \frac{4}{5} \alpha_p g_{o,pp}(1 + e_{pp}) \right]^2 \]  

(8.2)

Dilute viscosity of solids is

\[ \mu_{sat} = \frac{5}{96}\rho_p d_p \sqrt{\Theta_p \pi} \]  

(8.3)

Radial distribution function

\[ g_{o,pp} = 1 + \lambda = 3 \left[ 1 - \left( \frac{\alpha_p}{\alpha_{p,max}} \right) \right]^{1/3} \]  

(8.4)

Where particle concentration (\( \lambda \)) is defined as the ratio of particle diameter to distance between the particles, radial distribution function (\( g_{o,pp} \)) is interpreted as the dimensionless distance between the particles, \( \alpha_p \) and \( \alpha_{p,max} \) are the solids volume fraction and packing limit, \( e_{pp} \) is the coefficient of restitution, \( \Theta_p (m^2/s^2) \) is the granular temperature of the particle.

### 2.3.2 Newtonian viscosity model with feed total solids correction (Nf_s)

Further the modified viscosity model of Ishii and Mishima [34] i.e. with total solids correction [15-17] is used to measure the mixture viscosity (\( \mu_m \)) in another case. This is similar to the model used by Wang et al. [19], chu et al. [18]. They had used a scale factor of 3.8 in the model to increase the viscosity levels in cyclone as the original Ishii and Mishima model predicting low values of viscosity.

\[ \mu_m = 3.8 \left[ 1 - \frac{\alpha_p}{0.62} \right]^{-1.55} \]  

(9)

### 2.3.3 Newtonian viscosity model with feed total solids and fines correction (Nf_s f_c)

The effect of fine particles is high on the rheology of the mixture [3]. The increase in fines fractions can lead to very high viscosity of the suspensions. Therefore fines correction is needed for describing the slurry behavior through Newtonian formulations. In this paper, Ishii and Mishima [34] viscosity function is modified by including the fine fractions below 53 \( \mu m \). The equation (10) was obtained by calibrating against the measured viscosity data of various mineral slurries [33, 36].
\[
\mu_m = \left[1 - \frac{a_p}{0.62}\right]^{-1.55} \left(F_{p=53}\mu\right)^{0.39}
\]  

(10)

2.3.4 Non-Newtonian Herschel-Bulkley model with feed total solids correction (HB)

Due to the presence of high shear rates (\(\gamma\)) within the cyclone, there is a need for shear dependent viscosity model. To account this, a shear dependent Herschel-Bulkley (HB) viscosity formulation is used [32]. The HB model parameters i.e., yield shear stress (\(\tau_0\)), consistency (\(\kappa\)), flow index (\(n\)) are fitted from the experimental data of He and Laskowski [4] as shown in Figure 1. These parameters are dependent on magnetite solids volume fractions and correlated with the power law functions. This data consists of magnetite feed solids concentration varying from 5% - 30% by volume and particle size distribution of superfine magnetite.

\[
\mu_m = \frac{\tau_0}{\dot{\gamma}} + \kappa\dot{\gamma}^{n-1}
\]  

(11)

Fig. 1. (a) Comparing the experimental data of He and Laskowski [4] with the HB model parameters consistency (\(\kappa\)), flow index (\(n\)), yield stress (\(\tau_0\)) fitted.

2.4 Lagrangian Particle tracking (LPT)

In this model Lagrangian reference frame is used to solve the properties of discrete/dispersed phase particles along with continuous phase solved in Eulerian reference frame using Navier-stokes equation. Large number of spherical particles is tracked which includes discrete phase inertia, hydrodynamic drag, gravitational force for both steady and unsteady flows. Turbulence effect has been predicted on the dispersed particles due to turbulent eddies present in the continuous phase. The motivation behind the usage of LPT model in DMC is that the correctly simulated magnetite medium segregation will drive the coal particles separation. Hence the LPT for coal particle partitioning is acceptable.

2.4.1 Particle Force Balance

It involves prediction of discrete phase particle trajectory by integrating force balance in the Lagrangian reference frame by equating particle inertia to forces acting on the particle.
\[
\frac{du_x}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_s
\]  
(12)

\[
F_D = \frac{18 \mu}{\rho_p d_p^2} \frac{C_D \text{Re}_p}{24}
\]  
(13)

\[
\text{Re}_p = \frac{\rho d_p |u_p - u|}{\mu}
\]  
(14)

Where \( F_x \) is an additional acceleration due to shear lift force, \( F_D (u-u_p) \) is the drag force acting on the particle, \( C_D \) is the drag coefficient, \( u \) is the continuous phase velocity, \( u_p \) is the particle velocity, \( \rho_p \) is the particle density, \( \rho \) is the fluid density, \( \text{Re}_p \) is the Reynolds number.

3. Numerical simulation

A 350 mm Dutch State Mine (DSM) dense medium cyclone used for the experimental Gamma Ray Tomography (GRT) studies [6] is considered for simulations in this study. Actual DSM cyclone inlet starts with cylindrical section and converges to rectangular section. To avoid complexity, mesh created here is started with rectangular section. Same volumetric flow rate is maintained as in case of circular inlet. Feed size distribution of magnetite considered for the multiphase simulations are consisting 7 phases; 2, 7, 15, 23, 32, 54, 82 µm as suitable average size representation with a density of 4950 kg/m³. The volume fraction of each modelled size of medium in the feed boundary condition is set so that the cumulative size distribution matched to the cumulative size distribution of the medium used by Subramanian [6] and the total feed medium concentration and volumetric flow rates matched to Subramanian’s experimental conditions. Initially free surface between air and water (Air-core) is solved using volume of fluid (VOF) model. Multiphase model is changed to Mixture (ASM) model before introducing magnetite. Turbulence is modeled using Reynolds stress model (RSM). A bounded central differencing scheme is used to discretize momentum equations. Pressure is solved by using PRESTO. QUICK is used to solve dispersed phase transport equations. Fixed time step of 1.0x10⁻⁴ s is used in all the simulations. Inlet is set to velocity inlet and outlet has been set to pressure boundary condition. Air
back volume fraction of 1.0 is used on the overflow and underflow boundaries which enables the simulation to generate air-core by drawing air so that negative pressure can be maintained in the center region. A custom slip velocity function by using lift force and viscosity correction by granular model, Newtonian model with total solids correction, with fines correction and non-Newtonian Herschel-Bulkley viscosity models were implemented through user defined functions (UDF).

4. Results and Discussion

4.1. Mesh independence and flow field predictions

Using the VOF model coupled with RSM turbulence model, the air-core and flow field in a 350mm DMC cyclone has been predicted for three different meshes 100 K, 200 K and 400 K. A 3D body fitted grid with 100 K nodes is used in the initial simulations. A detail of the geometry and grid used for the simulation is given in Figure 2 a, b. Grid independence check w.r.to mean tangential and axial velocity is performed with different meshes generated by grid adoption using boundaries is shown in Figure 3. Displayed results are plotted across XZ plane and averaged over few thousand iterations equivalent to approximately 2 sec of physical time after reaching steady state, where net mass flow rate between feed, overflow and underflow is oscillating around zero) From the comparison, tangential velocity, axial velocity predictions by 200 K, 400 K nodes are almost similar whereas 100 K nodes are associated with lower magnitude of tangential velocity component. It is suggesting that for better predictions grid with ~200 K nodes is ideal for 350mm DSM cyclone.

Fig. 2. (a) Detailed dimensional drawing of the 350 mm DSM dense medium cyclone used for simulations, (b) with numerical grid.

Fig. 3. Predicted mean (a) tangential and (b) axial velocities by different mesh sizes at 0.47m from the top of cyclone, for a feed volumetric flow rate of 0.0105 m³/s using RSM turbulence model and VOF multiphase model.

4.2. Analysis of multiphase data
Figure 4.1 displays predicted mean medium density contours plotted across XZ plane in the DMC by CFD models having different rheological formulations corrected with lift and drag forces. From the contours it is clear that the magnetite segregation levels are very high with GV and HB models and are in good comparison with experimental GRT data. Density of suspension is calculated by accounting volumetric flow rate of slurry to volumetric flow rate of water and magnetite along with respective phase volume fractions. By monitoring the mass flow rates and manually averaging the data over few thousand iterations has provided the predicted mean density data as shown in Table 1. Experimental and CFD predicted underflow and overflow densities, underflow slurry volume recoveries of different viscosity models are compared in Table 1. This over prediction of \( R_m \) is resultant of the under predicted underflow densities. Prediction of underflow volume recoveries (\( R_m \)) of all the models are deviated with the data of experiments. GV and HB models are having closest value to the experiments. Flow densities predicted by HB model are close to wood model data. Fig 4.1 shows the air-core contour by Gamma ray tomography (GRT) data, where the scanning data was collected substantially longer periods than the particle and fluid residence times. Figure 4.2 depicts the comparison of axial variation of GRT measured air-core radius compared to modified CFD model predicted air-core radius. It can be observed that HB model predictions are very close at the top portion of cyclone but slightly under predicted towards the conical section. \( \text{Nf}_s \), \( \text{Nf}_s f_c \) models are over predicted the air-core radius in the cylindrical section and following similar behavior throughout the cyclone. GV model is over predicting the air-core size throughout the cyclone. From Fig 4.1 and 4.2, it is understood that the disposition of air-core behaves as oscillating steady state nature. Therefore it is believed that the variation of statistically averaged air-core predictions is almost depicting the steady state nature unless there is a variation in the feed flow characteristics. In reality the air-core is dynamically varying for a given instantaneous time.

**Table 1**

Mean flow densities predicted for 350 mm DSM cyclone compared to experimentally measured GRT densities
4.3. Prediction of medium segregation

At high solids concentrations (feed relative density of 1.465 which is equal to 39.65 wt%), the particle-particle interactions lead to a number of influences on the slurry flow behavior. The increased slurry viscosity levels, hindered particle settling velocities and additional generation of external forces on the particle due to varying degree of velocity gradients are associated with slurry flow behavior due to increased particle-particle interactions. In this section, the predictions of rheology based CFD models with standard ASM Model and modified ASM model with lift force are analyzed quantitatively and compared radially at different axial positions.

4.3.1 Algebraic Slip Mixture model (ASM)

Multiphase Simulations are initiated with standard ASM model [25] incorporated in ANSYS’s Fluent. The predicted mean radial density profiles at various axial positions are shown in Figure 5. From the Figure 5 it can be noted that, at all the axial positions the density predictions by the standard ASM model near the wall are over predicted. The mean densities near the air-core are under predicted compared to the experimental GRT values. The predicted density segregation levels in the bottom conical section are low compared to GRT data. To reduce the high density predictions near the wall, the simulations are further continued with the ASM model modified with respect to various rheological models as described in 2.3.

Fig. 5. Mean radial density profiles at 0.23m, 0.47m, 0.65m, 0.67m axial locations by ASM, Nf_s, Nf_sf_c, HB rheological models with standard mixture model for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m³/s.
4.3.2 Only rheology based CFD models

To address the suitable viscosity formulations for medium modelling in DMCs, three different viscosity models are tested with the standard ASM model. The results are presented in Figure 5. With the medium rheology modification, the wall densities are substantially lowered compared to Fluent’s standard ASM model. At 0.23m and 0.47m from roof of the cyclone, the density predictions of all the models are in agreement with GRT experimental data. In the conical section i.e. at 0.65m and 0.67m the mean densities are under predicted at most of the radial positions and wall densities are still over predicted compared to GRT data. All the modified ASM models with only rheology modifications are under predicting the densities at inner radial positions and over predicting at wall positions compared to experimental values in the conical section. It is believed that the solids concentration in conical section is high compared to the cylindrical section, which might be causing the discrepancy. Hence the correction with only rheology is not sufficient, additional forces are required to enhance the wall density profiles.

4.3.3 Rheology based CFD models with lift forces

To improve the predictions further, shear lift forces are added to the standard ASM model along with the rheology modifications. Simulations are also run with ASM model by enabling the granular options (available in Fluent). The mixture model granular option is a simplified version of full Eulerian granular flow model [41]. The mixture viscosity in the region of the cyclone has been calculated using the GV model. This viscosity model is similar to $Nf_s$ model in which it limits the solids concentration to a realistic value by driving the mixture viscosity to infinite when the total volume fraction of solids approaches 0.62 (the packing limit). However Gidaspow et al. [42] model also makes the viscosity shear dependent and granular temperature dependent. Here in this section the presented results include GV, $Nf_s$, $Nf_{fc}$, HB rheological models with slip velocity corrected by the lift forces. The model predictions are analyzed and the predicted slurry density profiles are compared to the experimental GRT data at different elevations as shown in Figure 6.

**Fig. 6.** Variation of mean densities along a radius at 0.23m, 0.47m, 0.65m by GV, $Nf_s$, $Nf_{fc}$, HB rheological models with modified mixture model corrected by lift forces for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m$^3$/s.
At a distance 0.23m from roof of the cyclone, the predicted densities by all the models between wall and air-core regions are in good agreement with GRT data (see Figure 6 a). Densities near the air-core are under predicted by GV, Nf_s and Nf_sfc rheology based CFD models. GV based CFD model density profiles are over predicted near the wall at all the elevations (Figure 6 a, b, c) compared to the GRT data. In case of HB model, although the wall densities are predicted close to GRT levels, because of high strain rates at the wall positions, this model is slightly over predicting the densities. The implemented HB model is having shear thinning behavior, which means that at high strain rates the predicted viscosities are low and hence low flow resistance for the particles prevails at these zones in the simulations.

Along the bottom conical section i.e. at 0.65m elevation, where the high medium concentration prevails, the predictions by GV and HB based CFD models are very close to experimental values. Density prediction by Nf_s formulation based CFD models at 0.47m is closely matching with experimental trend except near the air-core. But at bottom conical section of the cyclone i.e. 0.65m these model predictions are substantially deviating from the experimental values (Figure 6 d). In case of GV model the reason for over prediction of the slurry densities near the wall might be the prediction of lower viscosity values. This viscosity (flow resistance) problem is partially solved by Nf_s and Nf_sfc models by limiting the packing fraction. The over prediction of densities near the wall is minimized at 0.23m, 0.47m, 0.65m with Nf_s, Nf_sfc based CFD model and the same can be observed from Figure 6. The predicted under-flow stream densities by Nf_s and Nf_sfc based CFD models are much lower when compared to the GV model (table 1) predictions. To account the shear thinning behavior, non-Newtonian Herschel-Bulkley model formulation based CFD simulations are conducted. Due to the existence of high shear rates within the cyclone, Herschel-Bulkley model has predicted acceptable density levels w.r.to GRT data as it involves a shear dependent term. The same can be observed from the Figures 6 (c) and (d). With this HB non-Newtonian formulation based CFD model, the prediction of underflow densities are enhanced compared to Nf_s and Nf_sfc models. Over prediction of the medium densities near the wall and under prediction of the medium densities near the air-core is minimized with the HB rheology based CFD model. In the plots 6 (a), (b), (c) and (d), there is a similarity in the sudden raise of medium density near the cyclone wall by GV and HB model predictions, but the increasing level differs from GV to HB model. The density predictions near the air-core region have improved by HB rheology based CFD model compared to other models. Overall
prediction by the HB based CFD model corrected with lift forces are in close agreement with the GRT data. Although the density predictions by $N_f_s$ and $N_f_s f_c$ formulation based CFD models are following similar experimental trend, but it predicts significantly large deviation data at 0.65m in the conical section (Fig. 6 c, d) against the GRT data. Another drawback with these models is its association of over predicted cyclone overflow densities and under predicted underflow densities.

**Fig. 7.** Mean density profiles in the cyclone from 0.19m to 0.67m (a) along the Locus of Zero Vertical Velocities (LZVV) (b) along the cyclone wall by GV, $N_f_s$, $N_f_s f_c$, HB rheological models with slip velocity corrected by lift force for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m$^3$/s. (c) Schematic showing the lines used to extract the density data at LZVV and near the wall.

Figure 7 shows axial variation of medium density predictions by different rheology based CFD models with additional lift forces from 0.19m to 0.67m along the locus of zero vertical velocities (LZVV) and near the cyclone wall region. It can be observed that near the wall region all the model predictions are close to experimental values in the cylindrical section i.e. up to 0.23m. Moving down to the conical section i.e. from 0.23m to 0.67m deviations between the predictions of Newtonian rheology based CFD models, the non-Newtonian rheology based CFD model and the GV model can be observed (Fig. 7 b). Near the wall region, HB model is slightly under predicting the density values in the conical section compared to experiments. Pure ASM model is over predicting the densities in the cylindrical section and under predicting the densities in the conical section. Along the LZVV, all the models are showing a decline trend after 0.5m which is matching with experimental trend; although there is a deviation between the experimental and the CFD predicted density values.

### 4.4. Prediction of viscosity levels by different rheology based CFD models

The contours of predicted slurry viscosity by CFD models based on various medium rheological formulations are shown in Figure. 8. The predicted viscosity levels are very low in case of granular viscosity (GV) based CFD model, which is under predicted than the expected levels in dense medium cyclones. As shown in Figure 8 (b) and (c), this problem has been partially resolved by modified Ishii and Mishima models ($N_f_s f_c$ and $N_f_s$) with a scale factor for total solids correction with and without the fines correction (for particles less than 53 µm sizes). In Figure 8, the predicted viscosity levels of $N_f_s$ and $N_f_s f_c$
are then substantially increased compared to GV based CFD model predictions. As observed in Figure 4, in both the Nf_s and Nf_s f_c based CFD models the predicted medium density segregation levels are still significantly deviating from the experimental values; therefore a shear dependent non-Newtonian Herschel-Bulkley model is also implemented in this study. With the non-Newtonian base CFD model, the predicted viscosity levels are increased an order of magnitude compared to the other models (see Figure 8 (d)). Figures 8 (d) and 9 confirms that the predicted of viscosities by shear thinning HB model is mainly depends on the strain rates.

**Fig. 8.** Viscosity contours of (a) GV model (b) Nf_s model (c) Nf_s f_c model (d) HB model.

**Fig. 9.** Strain rate contours in the DSM dense medium cyclone.

Fig 10 depicts the comparison of CFD predicted viscosity data with the offline viscometer based experimental magnetite data of He [3] for increasing solids volume fraction. It can be observed that granular model predicted viscosities are almost all equal to water viscosity levels. Newtonian based CFD models have improved the viscosities even though the predicted viscosities are much lower than the experimental data. As the volume fraction levels are increased, a clear difference can be seen between Newtonian viscosity models and non-Newtonian based HB model. Due to lack of experimental results at particular location, the predicted viscosity levels by different rheology formulation based CFD models are compared among at 0.27m, 0.47m, 0.67m and 0.87m along the radial direction have shown in Figure 11. From Figure 11 (a), it is observed that the predicted viscosity level by GV model is mostly close to water viscosity value of 1 cp at all the axial positions. From Figures 11 (b) and 11 (c) i.e. with modified Ishii and Mishima model (Nf_s f_c and Nf_s) based CFD predicted viscosity levels are reached maximum values up to 4-6 cP. Predicted viscosity level by Nf_s based CFD model without scale factor is slightly greater than GV model but with a scale factor of 3.8 it reached values up to 6 cP. With Nf_s f_c based CFD model, the predicted viscosity level is further increased up to 4 cP without any scale factor. Reason behind the improvement of viscosity levels with Nf_s f_c model is inclusion of fines correction term, which is believed for having significant effect on the rheology. As shown in Figure 8 (d), with shear dependent HB model based CFD model, the predicted viscosity levels reached up to 7-12 cP. From the viscosity plots shown in Figure 11, further it is observed that viscosity is almost constant throughout DMC except in the conical
Due to the dominance of strain rates at the wall the predicted viscosity by HB model based densities are decreased near the wall compared to center region. Whereas Nf_s, Nf_s f_c models have simulated higher viscosity values in the bottom cyclone region compared to the cylindrical section due to the increased solids volume fraction levels. Enhanced medium viscosity predictions are observed mostly with the non-Newtonian Herschel-Bulkley model. Comparison of predicted viscosity levels and corresponding medium volume fractions by different rheological models at 0.67m is also shown in Figure 12 (a).

**Fig. 10.** Comparison of modified CFD model predicted viscosities with offline viscometer based experimental magnetite data of He [3] for different solids volume fraction.

**Fig. 11.** Comparison between viscosities at different locations i.e. at 0.27m, 0.47m, 0.67m and 0.87m by (a) GV model (b) Nf_s f_c model (c) Nf_s model (d) HB model for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m^3/s.

Predicted volume fractions and viscosities are compared between different rheology based CFD models at 0.67m axial elevation are shown in Figure 12 (a) and (b). From Figure 12 (b), it is observed that the best viscosity predictions are associated with non-Newtonian HB model in accordance to theoretical levels [4], indicated by offline viscometer measurement for the same medium. Although the medium segregation levels are very good by GV model compared to other models, the GV model suffers due to their low viscosity levels associated with medium (see Fig. 12 (b)). An increment in viscosity levels is observed with the modified Ishii and Mishima model (Nf_s, Nf_s f_c) based CFD predictions, shown in Figure 12 (b). Prediction of volume fractions by different rheology based CFD models is also shown in 12 (a).

From both graphs 12 (a) and (b) one can observe that there is an interaction between solids volume fraction and slurry viscosity levels in case of Nf_s and Nf_s f_c models. Strain rates are dominating the HB model viscosity predictions than the total solid fraction corrections especially in the cyclone conical section. This might be a reason for the under prediction of densities in the underflow. Non-Newtonian model including the solids volume fraction effect is continued with further research work. GV model has low volume fractions hence low viscosity predictions are observed. There is a sudden increase with the
volume fraction levels near the cyclone wall at 0.67m axial position, which might be the reason for sudden raise in the densities near the wall with GV and HB models.

**Fig. 12.** Variation of (a) volume fractions (b) viscosity levels at 0.67m by different rheological models for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m$^3$/s.

### 4.5. Prediction of coal partitioning

DPM model is used to predict the coal partition phenomena in DMC. 5 different sizes of coal particles with diameters 8, 4, 2, 1, 0.5 mm are used. 1000 particles with uniform diameter and sphericity of 0.8 are injected across the feed boundary using instantaneous flow field from RSM model coupled with modified ASM model for all the rheological models. The number of particles reported to the underflow is noted and used to generate partition curve as a function of particle density for a given particle size. The Lagrangian particle tracking is repeated 3 times and averages to obtain the mean value. The sharpness of cut of a DMC is characterized by Ecart probable ($E_p$), defined as follows:

$$E_p = \frac{\rho_{75} - \rho_{25}}{2}$$  \hspace{1cm} (13)

Where $\rho_{75}$ and $\rho_{25}$ are relative densities corresponding to 75% and 25% of feed material rejected to underflow. Figure 13 exhibits the predicted partition coefficients of different size particles with varying densities. Coarser (8mm) size particles are having lower $E_p$ compared to smaller size particles. This implies that it has high chances of separating with minimum misplacement to underflow/overflow depending on the particle density. Decreasing the particle size reduces the sharpness of cut and increases the $E_p$ value. Due to lack of experimental results on the coal partition in a 350mm DMC, predicted CFD results are validated against Wood DMC model [9]. Wood empirical model is based on the compendium of experimental data collected for the number of DSM geometries of DMC for a wide range of operating conditions. Therefore, this model is widely used in the coal preparation industries for predicting the performance of DSM based dense medium cyclones. 350mm DMC used in the present work is also a DSM design. Therefore, rheology based CFD model predicted cut density ($\rho_{50}$) are
compared with Wood DMC model predictions and shown is Table 2. It also contains predicted \( E_p \) of all the CFD models. From the table on can notice that, GV and HB model predicted cut densities and \( E_p \) are close to Wood model predictions. Whereas \( Nf_s \) and \( Nf, f_c \) model predictions are deviated from the DMC model predictions.

**Fig. 13.** Coal partition curves predicted by size and density in a 350mm DSM cyclone for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m\(^3\)/s.

### 5. Conclusions

1. Multiphase simulations in a 350mm DMC are conducted by using modified algebraic slip mixture model with shear lift forces and viscosity correction. Turbulence is modeled by RSM model. Viscosity correction has been incorporated using various rheology based formulations such as granular viscosity model, solids total volume fraction, fines corrected Ishii and Mishima models; non-Newtonian Herschel-Bulkley model.

2. ASM modified with rheology models shows realistic densities near the wall, especially in the conical section. Fines corrected CFD model with lift forces is under predicting the densities throughout the cyclone even though it follows experimental trend. Only feed solids corrected CFD model with lift forces predictions are close to experimental values near the air-core, but deviations are observed in the conical section where the solids concentration is high.

3. Granular viscosity based CFD model predictions are closely matches the experimental data except at the walls. The improved predictions are observed for the medium segregation in the DMC by the non-Newtonian HB based CFD model compared to all the other rheological based CFD models.

4. Total feed solids and fines correction below 53\( \mu \)m based CFD models are successfully predicted viscosity levels up to 8 cP whilst underflow densities are under predicted and overflow densities are over predicted in both cases.

5. In spite of very good density predictions with GV model, the predicted viscosity levels are significantly low. But in case of non-Newtonian Herschel-Bulkley based CFD model, the predicted viscosity levels
are appropriate and the predicted values of densities are closed to experimentally measured gamma ray tomography data. The predicted viscosity has increased up to 18 cP with Herschel-Bulkely based CFD model. HB model predicted $d_{50}$ and $E_p$ are close to wood model [9] predictions. Overall volume split to underflow by all the rheology models are deviating from the experiments.

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Fig. 6. Variation of mean densities along a radius at 0.23m, 0.47m, 0.65m by Nf_s, Nf_sf_c, HB rheological models with modified mixture model corrected by lift forces for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m^3/s.

Fig. 7. Mean density profiles in the cyclone from 0.19m to 0.67m (a) along Locus of Zero Vertical Velocities (LZVV) (b) along the wall by GV, Nf_s, Nf_sf_c, HB rheological models with slip velocity corrected by lift force for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m^3/s. (c) Schematic showing the lines used to extract the density data at LZVV and near the wall.

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Fig. 12. Variation of (a) viscosity levels (b) volume fractions at 0.67m by different rheological models for feed relative density of 1.465, feed volumetric flow rate of 0.0105 m^3/s.
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Table 1
Flow densities predicted for 350 mm DSM cyclone compared to experimentally measured GRT densities

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Table 2
Predicted cut densities, Ecart probable (Eₚ) for 350 mm DSM cyclone compared to Wood DMC model.

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Graphical abstract

LPT (Coal partitioning)

CFD model for medium segregation

Turbulence modeling (K-Ω)

None Newtonian based CFD Model

GRT data

+
Highlights:

- Dense medium cyclone is modeled with rheology based CFD models with extra forces
- Granular, modified Newtonian & non-Newtonian viscosity based CFD models are tested
- Predicted density contours are compared with experimental gamma ray tomography data
- Medium segregation is well predicted by Herschel-Bulkely & Granular viscosity models
- Herschel-Bulkely viscosity based CFD model predicts high viscosities