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CFD STUDY ON THE EFFECT OF NEAR GRAVITY MATERIAL ON DMC TREATING COAL USING DPM AND ASM MULTIPHASE MODEL

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ABSTRACT

The difficulty in washing of coal is very much influenced by the amount of near-gravity materials (NGM) present at the desired cut density. It is believed that the dense medium separation of coal particles in the presence of a high percentage of NGM results in a significant misplacement of coal particles to wrong products. However the performance of dense medium cyclone (DMC) does not merely depend on the total amount of near gravity materials but also on their distribution as well as on their quality. In this paper, numerical simulation of magnetite medium segregation and coal partitioning has been made in a 350 mm diameter cyclone. An attempt is made to assess the nature of impairment in efficiency in relation to the increasing amount of near gravity materials in coal.

The CFD model uses the Algebraic Mixture model with the granular option and Reynolds stress model (RSM) to resolve the air core and turbulent mixing of the medium and coal particles. The partition characteristics of the DMC were modelled using both Lagrangian and Eulerian particle tracking for particles ranging in size from 0.5 to 8 mm and in density from 1200 to 2000 kg.m^{-3}. Specifically near gravity density particles having different mass proportions are tracked inside DMC. The effect of NGM fraction on overall cyclone performance and product density differential was studied. It is observed that smaller size (-0.5 mm) coal particles having high NGM content seem to have a significant misplacement in a DMC.

INTRODUCTION

Most Indian coals have difficult washing characteristics due to high ash levels and presence of high portion of near-gravity material (NGM), which is defined as the portion lying within ±0.1 relative density (RD) of chosen cut density. The presence of NGM and their course of movement influences the separation gradient which directs coal particles to wrong product. As a result dense medium separator's performance decreases due to the misplacement caused by NGM content of the given coal.

Dense Medium cyclones (DMCs) are the devices used for efficient separation at any desired specific gravity and they are very effective in treating coals having high NGM content. DMC is an efficient gravity based separator, employing the use of a dense medium, a suspension of superfine/ultrafine magnetite and water. The specific gravity of the suspension, i.e., the separating fluid is adjusted to be between clean coal and associated mineral matter densities for coal preparation plants.

In DMC, the feed material, i.e., mixture of raw coal and medium, enters tangentially near the top of the cylindrical section, thus forming strong vortex flow. The centrifugal force associated with vortex flow causes the high dense particles to move along the wall and discharge as underflow. The drag force causes the low density clean coal to move towards longitudinal axis and discharge as overflow. The existence of medium and coal as well as the dominance of turbulent flow of different particle size, various proportions of near-gravity material and density effects on separation makes the flow in DMC very complex. Previous computational work shows significant progress in understanding the nature of flow in the presence of a medium, but the coal and medium interactions with respect to NGM is not understood. In this paper, an attempt is made to study the DMC flow behavior in the presence of coal with medium and the effect of NGM particles on overall cyclone performance.

PREVIOUS WORK

Literature on NGM effect on DMC performance is very scarce. Sarkar et al. (1959) studied the effect of near gravity material in a 6 in. diameter cyclone and at a cut density of 1.5 RD shows that an increase in near gravity material has an adverse effect on cyclone performance and the cut density varies. It is also shown that an increase in distribution ratios of near gravity material decreases separation efficiency of the particles resembling misplacement of particles. Studies by Sripriya et al. (2007) on treating the coal of high NGM at an optimum feed rate showed that increased long residence time distribution of coal particles by reducing the spigot diameter, increases the separation efficiency. de Korte (2008) proposed a new definition for NGM, i.e material lying in the density range of ± 2 × Ecart Probable Moyen (EPM) from the cut point density and observed that an increase in NGM content increases the misplacement of the particles particularly at smaller sizes of the particles. Studies by Magwai and Classen (2010) showed that an increase in cyclone diameter and blending of high NGM with low NGM coal increases the efficiency in treating the coal at high percentages of NGM. Studies by Meyers et al. (2014) on NGM showed that low values of medium to coal ratio (M:C) increases the separation efficiency for high near-gravity at low density separations. In order to understand NGM content on DMC performance fundamentally it is important to study coal particle trajectories inside the DMC.

Based on fundamentals of fluid flow and computational fluid dynamics (CFD), mathematical models are developed and explored for DMC over the last two decades. The first model by Zughbi et al. (1991). was a simplified approach with an assumption of axis symmetry and Prandtl mixed length turbulence model shows approximate values of axial and tangential velocities when compared with Smith correlations. Suasnabar and Fletcher (1998) proposed a 2D model for 200 mm DMC with an assumption of air fluid interface as a slip wall and k-ε, modified k-ε, Reynolds Stress Model (RSM) were adopted to resolve the turbulence inside the cyclone. The model developed by Narasimha et al. (2006), in a 350mm DMC well described the density distribution and in comparison with different turbulence models such as RSM, DRSM and Large Eddy Simulation (LES). A precise air core position and accurate mean and fluctuating velocity prediction are observed with LES turbulence model.

An efficient model is required for simulating multiphase flow in DMC. There are number of multiphase models available in CFD for simulating such complex flow behaviour. 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. Suasnabar and Fletcher (1998) uses Eulerian frame for modelling the medium segregation and Lagrangian frame for tracking the coal particles. Brennan et al. (2002) uses ASM model with an average medium particle size to describe DMC flow results in large deviation in medium segregation in comparison with experimental data. Narasimha et al. (2006), (2007) attempted DMC modelling with full magnetite particle size distribution (PSD) and modified the Algebraic Slip Mixture (ASM) model by adding shear lift forces and Newtonian viscosity correction. Narasimha et al. (2006a) successfully modelled the pivot phenomena in which all partition curves pass through a similar pivot point using Lagrangian Particle Tracking (LPT) method for coal particles. It was observed a small deviation in separation density due to the assumption of dilute coal concentration whereas in practical this deviation was not shown due to interaction between the particles. Wang and Yu (2006) showed that segregation of coarse magnetite particles in the medium occurs at the spigot and the distribution of different density coal particles in DMC is stratified along the axial direction. Surging may arise due to instability of medium flow which may result from improper DMC design or operation. The absence of particle-particle interactions in LPT method can be resolved using Discrete Element Method (DEM). Chu et al. (2009) proposed a one-way coupling method CFD-DEM with an assumption of ignoring particle flow reaction on medium flow. As this model requires huge number of particles which is computationally expensive, Chu et al. (2009a) proposed a two-way coupling CFD-DEM model, the concept of introducing parcel particles. As parcel particles are not real and it is difficult to understand the fundamentals clearly, so a detailed and realistic work is needed yet to simulate the coal particles. Despite numerous numerical studies made in the past, no attempt has been made so far to address the NGM particle behaviour in DMC's.

PRESENT WORK

In the present paper, numerical simulation of magnetite medium segregation and coal partitioning has been made in a 350 mm DSM cyclone for various NGM fractions. The partition characteristics of the DMC were modelled using both Lagrangian and Eulerian particle tracking. Initially medium segregation is simulated using modified ASM model. After the multiphase simulation of the medium is converged the coal particles were injected at the inlet using LPT approach superimposed on the ASM model. For full Eulerian model, eleven phases are used of which five phases are coal fractions of different density, four phases are magnetite medium fractions of different sizes, and the remaining two phases are water and air. These simulations are carried out for 0.5 mm size coal particles and at different amounts of NGM in coal (35%, 45% and 60%). The mean converged data is used to characterize the DMC performance, mainly the NGM effect on overall mixture density profiles, individual volume fraction profiles of coal and medium.

METHODOLOGY

The CFD approach used here is same that used by Narasimha et al. (2006). The coal and magnetite particles that are dispersed in water are considered as dispersed phases and water as the continuous phase in all simulations. The flow turbulence is modelled using RSM to resolve the turbulent mixing, and the interface between air core and medium is solved using the Volume of Fluid (VOF) technique, in order to obtain the primary position of air core and velocity distribution which can be used as initial conditions to speed up the next step computations in a way similar to the hydrocyclone multiphase modelling by Wang and Yu (2006). Once the formation of air core is completed, further modelling is carried out using both LPT and full Eulerian model.

LAGRANGIAN APPROACH

In LPT model, initially the medium is modelled using Algebraic Slip Mixture (ASM) model. Six phases of magnetite of different sizes (2.4, 7.4, 15.4, 32.2, 54.1 and 82.2 μm) are introduced as dispersed phases along with air moving through the continuous phase, water. These phases are simulated by the mixture model along with a correction of viscosity effect of different particle sizes of magnetite. As a base model, calculations are performed with basic granular viscosity (GV) formulation incorporated in Fluent which has been proposed by Ding and Gidaspow (1990). Details of granular viscosity formulation incorporated in Fluent manual (2011). The results obtained from the above step are then utilized for tracking of coal particles using the discrete phase model (DPM) for particles ranging in size from 0.25 to 8 mm with density ranging from 1200 to 2000 kg.m^{-3}. From the coal particle tracking data, DMC separating performance is characterized with partition co-efficient curve and medium split.

MIXTURE MODEL

The mixture model (Manninen et al., 1996) is a modified single fluid approach. The mixture model allows the phases to move at different velocities. The continuity equation for the mixture is

$$\frac{\partial}{\partial t}(\rho_m) + \frac{\partial}{\partial x_i}(\rho_m u_m) = 0 \quad (5)$$

where u_m is the mass- averaged velocity

$$u_m = \frac{\sum_{q=1}^{n} \alpha_q \rho_q u_q}{\rho_m} \quad (5a)$$

and ρ_m is the mixture density α_q is the volume fraction lying in the range between 0 and 1

$$\rho_m = \sum_{q=1}^{n} \alpha_q \rho_q \quad (5b)$$

The momentum equation for the mixture can be obtained by summing the individual momentum equations for all phases.

$$\frac{\partial}{\partial t}\rho_m u_{mi} + \frac{\partial}{\partial x_j}\rho_m u_{mi} u_{mj} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\mu_m\left(\frac{\partial u_{mi}}{\partial x_j} + \frac{\partial u_{mj}}{\partial x_i}\right) + \rho g_i + \frac{\partial}{\partial x_j}\left(\sum_{q=1}^{n}\alpha_q \rho_q u_{dr,qi} u_{dr,qj}\right) \quad (6)$$

where n is the no. of phases and μ_m is the viscosity of mixture

$$\mu_m = \sum_{q=1}^{n}\alpha_q u_q \quad (6a)$$

where $u_{dr,q}$ is the drift velocity for secondary phase q, which is defined as the velocity of dispersed phase relative to that of volume centre of mixture, given $\mathbf{u_{dr,q} = u_q - u_m}$. As diffusion velocity the drift velocity is also determined from relative velocity which is also known as slip velocity.

DPM MODEL

The motion of coal particles is defined by the so-called Lagrangian multiphase flow model. The pressure and drag forces on particles are calculated in a Lagrangian frame. The velocity distribution of particles can be evaluated the force balances on the particle. The governing equation is as follows

$$\frac{du_p}{dt} = F_D\left(\vec{u} - \vec{u_p}\right) + \frac{g(\rho_p - \rho)}{\rho_p} + F_x \quad (7)$$

where $F_D(\vec{u} - \vec{u_p})$ is the drag force per unit particle mass

$$F_D = \frac{18\mu_m}{d_p^2 \rho_p} C_D \frac{Re_p}{24} \quad (8)$$

$$Re_p = \frac{\rho d_p |u_p - u|}{\mu} \quad (9)$$

where F_x is an additional acceleration due to shear lift force, $\vec{u_p}$ is the particle velocity, $\vec{u}$ is the velocity of the fluid, ρ_p is the density of the particle, and d_p is the diameter of the particle, C_D is the drag co-efficient, and Re_p is the relative Reynolds number.

EULERIAN APPROACH

In full Eulerian model simultaneously both coal and magnetite particles are modelled using the ASM model. Along with water and air four phases of magnetite of different sizes and five phases of coal of different densities are introduced as dispersed phases. ASM model along with a correction of viscosity effect is used for modelling. The simulations are carried for 0.5 mm coal size at different fractions of NGM content (35%, 45% and 60%) in coal. From this simulated data the DMC separating performance is characterized in the presence of near-gravity material.

Thus the whole strategy involves four CFD model components and one viscosity correction model.

NUMERICS

For CFD simulation, a 3D structure of the 350mm DSM used by Subramanian (2002) for Gamma Ray Tomography (GRT) studies is employed. The grids that are used in the simulation are similar to the grids used by Narasimha et al. (2006) and Reddy and Mangadoddy (2014).

For momentum equations a bounded central differencing scheme, for pressure, PRESTO and QUICK for dispersed phase transport equations are used for discretization. A fixed time step of 1.0×10^{-4} s is used for the simulations. The boundary condition for inlet is velocity and for outlet is pressure. Air back-flow 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 centre region. A custom slip velocity function corrected with lift forces and viscosity correction was implemented using UDF's.

The mixture velocity is given by the fallowing equation

$$\mu_m = 3.8 * \left[1 - \frac{\alpha_p}{0.62}\right]^{-1.55} \quad (10)$$

where α_p is the solids volume fraction. The above equation is the modified viscosity model of Ishii and Mishima (1984)

The physical properties of the fluid phases are shown in Table 1. Six phases of magnetite of different sizes (2.4, 7.4, 15.4, 32.2, 54.1 and 82.2 μm) are set up in the mixture model at the operating conditions shown in Table 2. The volume fraction of each size and cumulative size distribution are considered similar to experimental conditions by Subramanian (2002)

Table 1: properties of the fluids

Property	Water	Magnetite	Air
Density, kg/m^3	998	5000	1.25
Viscosity, kg/m s	0.00103	0.003	1.7894* 10^{-05}

Table 2: operational conditions of simulations at different feed densities

Feed density, kg/m^3	Head (D_c, diameter of the cyclone)	Volumetric flow rate, m^3/s
1300	9	45.7
1465	9	47.5

Table 3: Volume fraction of coal used in simulation

Specific gravity of coal	Volume percent of coal at different NGM percentage in feed		
	35%	45%	60%
1.3	2.09	2.44	3.21
1.35	1.48	2.14	2.81
1.4	1.73	2.42	3.18
1.45	2.11	2.44	3.21
1.5	12.59	10.57	7.59

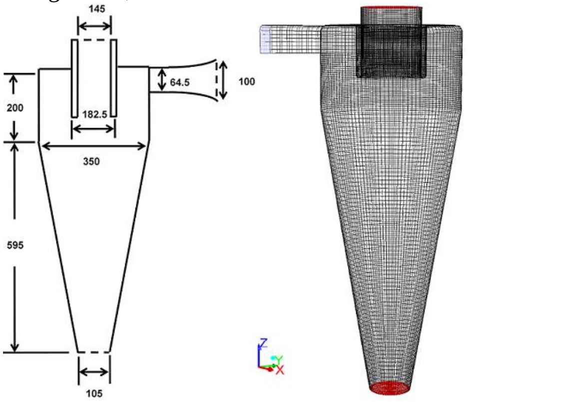
Once the medium reaches transient steady state, 1024 coal particles are injected continuously as discrete phase for particles ranging in size from 0.25 to 8 mm with varying density from 1200 to 2000 kg.m^{-3}. The maximum number of steps used is $5*10^7$ with shape factor of 0.8 and Saffman lift force physical model. The tracking schemes consists of trapezoidal rule for high order and implicit for low order in an absolute frame. The turbulent dispersion is modeled using discrete random walk model (DRW) with random eddy lifetime. After collecting the number of coal particles reported to overflow and underflow, the partition number is calculated using standard coal partioning curve and the performance indices are evaluated.

The input data of volumes fractions of coal is shown in Table 3. From the simulation data the DMC performance with NGM is analyzed using mixture density profiles and individual coal and medium particle distribution profiles.

RESULTS AND DISCUSSION

Mesh independence and flow field predictions

The flow field and air-core for 350mm DMC cyclone is predicted for three grid sizes 100 k, 200 k and 300 k and results for flow field predictions are similar to those done by Reddy and Mangadoddy (2014). An optimum size of ~200 k grid size for a 350 mm size cyclone is suggested for better flow field predictions with RSM turbulence model. A detailed geometry with numerical grid is shown in Figure 1 a,b which is used for simulation.



(a) (b)

Figure 1: (a) Detailed geometry of DSM cyclone with (b) numerical grid of 200k

Analysis of coal using DPM Model

Magnetite Segregation predictions

To study the present work, the data presented by Narasimha et al. (2006) and Reddy and Mangadoddy (2014) was taken for the feed of 1.3 RD and 1.467 RD. The magnetite segregation predictions shown by the authors are in good agreement with GRT experimental data of Subramanian (2002).

Coal Partitioning

Using DPM superimposed on medium simulations, the coal partitioning is made for RD 1.3 and 1.467 and shown in figures 2. It is shown that the cyclone is more efficient for the large size particles than for the small size particles. And it is also shown that the particle with more density far away from cut point density are going to underflow and less dense particles to overflow with more efficiency. But the particle having the density close to the cut point density shows less efficiency to pass through their respective exits. An attempt is made to understand particle behaviour whose densities are close to the cut point densities by their residence time inside the cyclone. A graphical representation of particle RTD versus density and RTD versus particle size is shown in figures 3 and 4 for feed of RD 1.3.

Figure 3 shows the residence time variance w.r.t to density for feed of RD 1.3. The low and high density particles showing less residence time and particles density close to cut point density referred as near gravity materials, showing long residence time which is in agreement with the literature. Due to this long residence times the misplacement of particles may result which in turn affects the efficiency of the cyclone. It is also shown that the small size particles are having longer residence time compared to large size particles. Figure 4 shows the maximum value of residence time w.r.t particle sizes. The maximum values of residence times for both feed RD's occurs near to their respective cut densities. But when comparing residence with feed RD, the longer residence times are with RD 1.467 than with RD 1.3. The increase in residence time w.r.t RD may be due to increase in medium volume fractions which causes the over predictions of densities near to the cyclone walls.

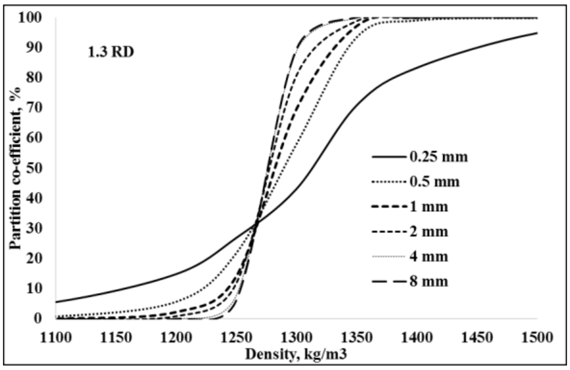


Figure 2: Partition curve for the coal particles of feed RD 1.3

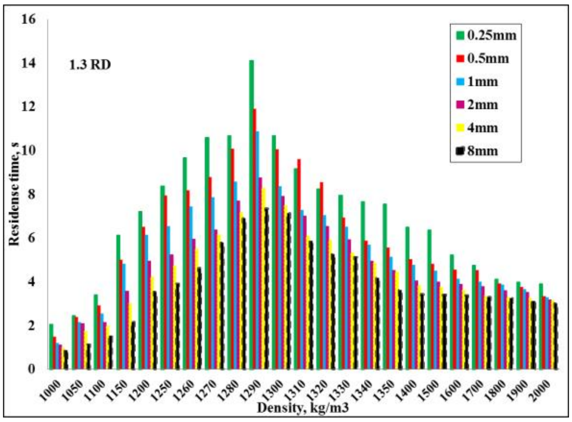


Figure 3: RTD versus density for feed of RD 1.3

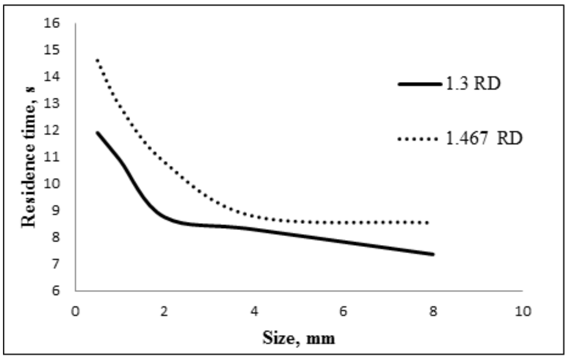


Figure 4: Comparison of residence times w.r.t size at RD's of 1.3 and 1.467

Analysis of coal using mixture model

Magnetite segregation

Predicted distribution of magnetite and coal is presented at different percentages of NGM of coal size 0.5mm. Figure 5 represents the predicted mean feed mixture density contours at different NGM content. A small variation is observed at vortex finder region. A quantitative representative of same w.r.t to radial direction is shown in figure 6 at different vertical positions of cyclone namely 0.27m, 0.47m, and 0.61m. It is observed that at axial position of 0.27 m the density increases with increasing NGM content near to the air core. This is may be due to accumulation of more near gravity coal particles. And moving towards to the conical section the density slightly increases towards the air core. This may be due to the accumulation of high volume fractions of high density coal particles. This may result in increasing the residence time of coal particles and misplacement of particles, which can influence the separation efficiency.

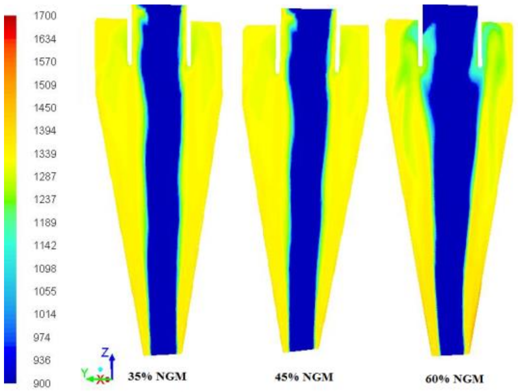


Figure 5: Mean-Mixture density distribution at different NGM content

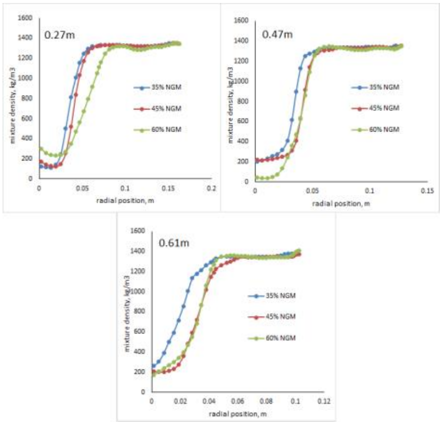


Figure 7: Mean-Mixture density profiles at different NGM content

Figure 8 shows a comparison between locus of zero vertical velocity (LZVV) profiles for only water, only medium and for overall medium and coal simulations at different radial positions. According to equilibrium orbit theory, Kelsell, (1952), the particle position outside LZVV reports to underflow and inside LZVV reports to overflow. Shifting of LZVV towards wall is observed in coal plus magnetite simulations. The shifting may be due to the coal particle segregation inside the cyclone. And w.r.t to increase in NGM content, this shift increases, reason may be due to the accumulation of high volumes of near gravity coal particle towards the air core.

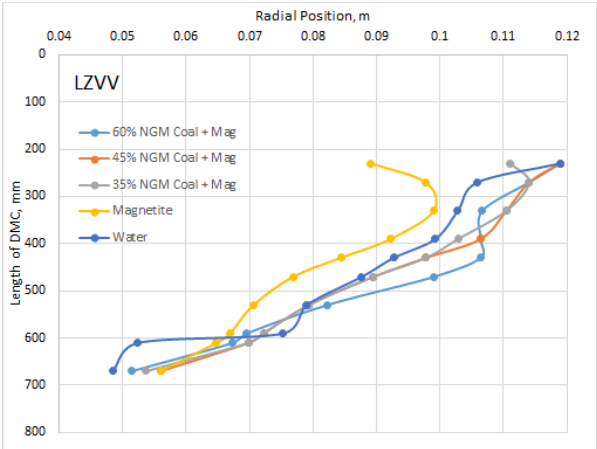


Figure 7: Comparative LZVV profiles of only water, only medium simulation and overall medium and coal simulation

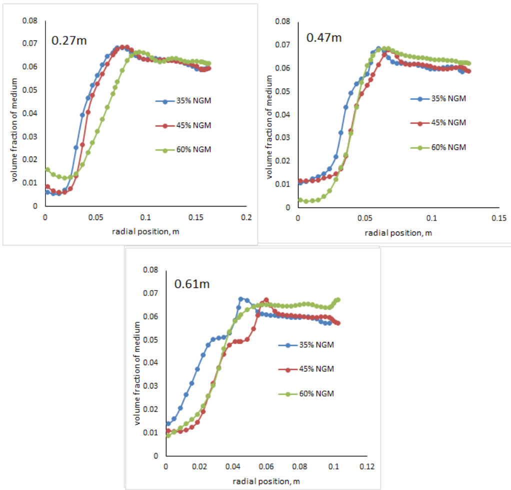


Figure 8: Overall mean magnetite distribution profiles

Figure 8 represents the overall magnetic volume fraction with respect to radial positions at different axial positions. It is also observed that towards air core the volume fraction of magnetite is less as NGM content increasing. And going towards the conical section the volume fraction of magnetite increases towards the wall but slight drop in density is observed at the wall. This is may be due to the accumulation of high percentage of high dense coal particles along the wall. This result may affect the medium flow and leads to misplacement of particles.

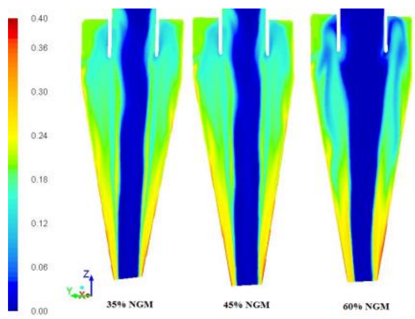


Figure 9: Overall mean coal volume distribution contours

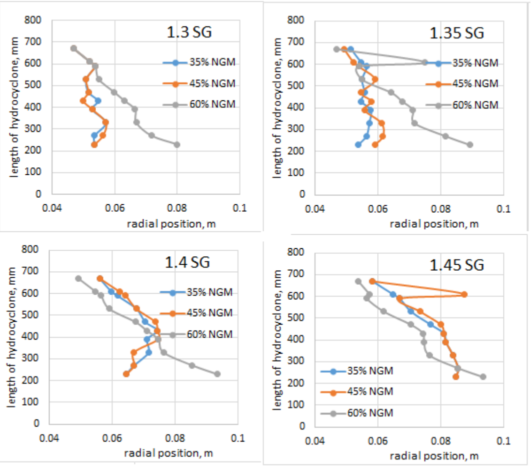


Figure 10: Mean position of Maximum Volume Fraction at particular SG

Fig 9 represents the contours of coal volume distribution with increased NGM content. With 35% and 45% NGM content the coal volume is more at air-core and cyclone wall near to the spigot. But with 60% NGM content the coal volume is distributed along the space between the air-core and cyclone wall near to the spigot. Fig 10 represents the mean position of maximum volume fraction of coal at a particular specific gravity (SG) with increased NGM content. With 35% and 45% NGM content coal concentration is high near to the air-core for SG 1.3 and 1.35 and for SG 1.4 and 1.45 the concentration is more near to the cyclone walls. With 65% NGM content a distributed coal concentration is observed from air core to cyclone wall at all SG of coal. From fig 9 and 10 with 35% and 45% NGM content it is observed the accumulation of NGM coal is more at the air-core which affects the flow of other coal particles other than NGM coal. This affect may results in increased residence time of coal which may cause the misplacement to wrong products. But with increased NGM content i.e, at 60% the accumulation of NGM coal is more and distributed along the space between air core and cyclone wall which is clearly shown in fig 9 and 10. This accumulation effect more for flow of coal particles other than NGM coal leads to misplacement and also reduces the separation efficiency. Thus with high NGM coal content it may be difficult to separate clean coal at all relative densities.

CONCLUSION

- Magnetite medium segregation is simulated using modified ASM model coupled with RSM turbulence model successfully and the same validated against the GRT data (Subramanian, 2002)
- DPM model is run superimposed on the converged medium simulations for the coal particle trajectories inside the DMC and an attempt is made to understand the RTD of different size and density coal particles.
- Coal particles having density near to separation-density exhibit increased residence time compared with other particles.
- As expected the smaller size coal particles show higher residence time than the coarse coal particles.
- CFD simulations on the effect of NGM fraction are initiated using ASM model including for coal and magnetite.
- Coal particles with high NGM content show significant effect in misplacement of coal particles towards wrong products at all relative densities.

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