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A CFD MODEL FOR DENSE MEDIUM CYCLONES

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ABSTRACT

In this paper, a CFD modelling strategy is described in detail. Then the paper focuses on studying the effect of the non-Newtonian rheology and turbulence phenomenon in the medium modelling. Therefore, fluid flow modelling is carried out for the Herschel-Bulkley and Power Law rheological models and compared with the Newtonian model with and without turbulence. Results for axial and velocity profiles show that the turbulence effect is more important than the non-Newtonian rheology. Consequently, a Newtonian model is developed for the medium for the case where the segregation of the magnetite particles in the medium can be neglected. Also a model for the coal particles is presented and combined with the medium model to give a practical model for DMCs. The model is an Eulerian-Lagrangian approach. Finally the model is used to evaluate the influence of coal particles size on the separation process. Coal particles of 5 mm and 1 mm diameter were considered. Predictions show the degradation of the efficiency of separation for smaller coal sizes. Also low density coal particles are initially affected by the recirculation region. Finally, higher residence times were found for neutrally-buoyant particles

NOMENCLATURE

u_i	velocity component in i direction
p	pressure
g_i	gravity component in i direction
ν	kinematic viscosity
μ	dynamic viscosity
μ_l	dynamic laminar viscosity
ρ	density of the fluid
$\dot{S}$	strain rate
τ	shear strain
τ_o	yield strain
ρ_p	density of the particle
C_D	drag coefficient
D_p	diameter of a particle
r	coefficient of correlation
u_{pi}	velocity of the particle in i direction

INTRODUCTION

Dense medium cyclones (DMCs) are widely used coal-cleaning devices in the mining industry. For hard-to-clean (+10% near gravity material) in the size range of 50 mm to 0.5 mm, DMCs are very effective. In operation, the raw coal and the medium are fed at a precise pressure into the tangential inlet. The ensuing flow spirals towards the apex of the device. In the core of the cyclone, a very fast upward flow is created. Centrifugal classification causes shale to move outwards towards the inner wall of the conical shell. As a result, shale is discharged from the apex and coal is carried by the rising internal spiralling flow towards the vortex finder to be discharged from the overflow.

Experimental studies, empirical and analytical modelling and computational modelling of the fluid flow pattern, pressure drop, and solids motion in hydrocyclones have been carried out by many researchers (Kesall, 1952; Pericleous and Rhodes, 1986; Hsieh, 1988; Davidson, 1994; Devallapalli and Rajamani, 1996; He, 1999). However, for DMCs such information is very limited. DMCs have been mainly subjected to experimental and analytical studies (Davis, 1987; Napier-Munn, 1990; Wood, 1990). Within the experimental studies, only parametric studies analysing the influence of geometrical and operating variables on the efficiency of separation are reported. The utility of this information is limited. Reported computational modelling of DMCs is virtually non-existent (only Zughbi et al, 1991). Having a reliable computational model for DMCs can assist in the improvement of the design and operating conditions, essentially enhancing the experimental approach.

Within the research context of improving the understanding of DMCs by means of computational simulation, this paper discusses our modelling approach and analyses the effect of the non-Newtonian character of the medium. Having found that a Newtonian approximation for the medium is valid, a CFD model for DMCs is proposed based on a composite medium with ultrafine magnetite. The CFD commercial code FLUENT is used to construct the CFD model.

MODEL FORMULATION

Fluid flow and particle interactions in DMCs are very complicated phenomena. Broadly speaking three phases can be distinguish. They are water, solids (magnetite, coal and waste particles) and air. However, from a numerical point of view different density and size particles must be considered as different phases. Hence, the complexity of constructing a model for DMCs is obvious; and a simplified treatment of the phenomena is appropriate.

Under normal operation, the vortex flow within the cyclone body generates an air core along the entire axis of the body. The air core has been modelled to be approximately cylindrical in shape and axially centred (Suasnabar and Fletcher, 1998). As a consequence, the air-fluid interface can be assumed fixed and may be numerically approximated as a slip wall. Also for a particular DMC geometry, modelling of the slurry at different specific gravities can be carried out with the same fixed air core diameter, since Wood (1990) found that the air core shape and size are independent of the density of the slurry.

With the simplified treatment of the air core, further simplifications are required for the fluid composed of water, magnetite particles and raw coal particles. For modelling purposes, the magnetite-water mixture may be separated from the raw coal particles. Then separate models can be formulated for the medium and coal particles. However, the models must interact with each other to produce an overall model for DMCs.

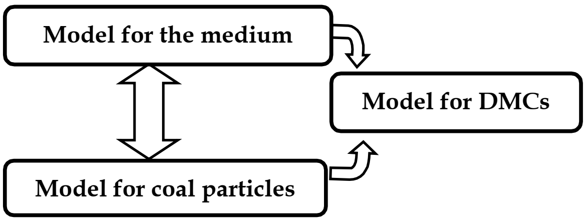

Figure 1: A modelling strategy for DMCs.

Modelling the medium can be carried out with different approaches. In the simplest approach, the medium may be assumed to be a homogeneous Newtonian fluid. A slightly more complicate model would be to consider it as a homogenous non-Newtonian medium. A more comprehensive approach would be a multiphase model. Following the traditional engineering philosophy, models are required to be simple but able to reproduce the experimental results. Also, simple models will be feasible to be used for performance improvement without much computational restriction. Consistent with this aim, analysis of the features of the magnetite medium is carried out below and in the next section.

The magnetite medium is made of magnetite particles dispersed in water. Several types of magnetite are used in practice. They are characterised in terms of the Rosin-Rammler intercept at 63.2% passing size in the recirculating media (designated as p). Typically fine (p=35μm), superfine (p=31μm) and ultrafine (p=26μm) magnetite particles are found in the field (Wood, 1990). Additionally, specific gravity for the medium ranging from 1.2 s.g. to 1.7 s.g. is usually used in practice. As described by He (1994), the density differential between the apex and vortex finder medium are higher when the density is lower and coarser magnetite particles are used. For example, from his results one can obtain that for a medium of superfine magnetite with 1.5 s.g., the underflow density is about 1.7 s.g and the overflow density is about 1.3 s.g.. Therefore, the density differential is approximately 0.4 s.g. If ultrafine magnetite of p=18μm is used instead and the density is increased to 1.6 s.g., the overflow density is about 1.6 s.g. and the underflow density is approximately 1.5 s.g. Then, the differential density for this case is only 0.1 s.g. As a consequence, a medium made of ultrafine magnetite particles and at high density (over 1.5 s.g.) can be assumed homogenous. Then a CFD model for the medium for this particular case can be constructed assuming homogenous fluid. Now the question is whether to assume a Newtonian fluid for this medium. Analysis of this issue is addressed in the next section.

Modelling of the raw coal particles may be a difficult task. Since the range of sizes and densities of the particles is quite large it is difficult to use an Eulerian continuum model. Additionally, in order to reproduce partition curves, a real representation of the raw coal particles can not be obtained by an Eulerian model due to computational limitations. Eulerian models may only be used to evaluate one or two monosize and/or monodensity coal particle separations at very high concentrations. Thus the Lagrangian approach appears to be the more appropriate alternative. Since mainly particle-particle interactions are difficult to account for in a Lagrangian reference frame, only dilute concentration calculations may be accomplished. However, if clouds of particles instead of single particles are tracked (Devulapalli and Rajamani, 1996), a high concentration of coal can be considered. In the latter model, concentration profiles within the cloud are approximately represented by a probability density function (pdf). Coal particle tracking at dilute concentration can be considered an approximation of the density tracer method (Davis, 1985). In this paper, only a model for coal particles at dilute concentrations is presented. Future models will consider more comprehensive models.

NON-NEWTONIAN RHEOLOGY ANALYSIS FOR THE MAGNETITE MEDIUM

To what extent can the medium be considered Newtonian?. This question can be only answered by analysing the influence of non-Newtonian rheology on the modelling process. Therefore in this section, we focus on a more detailed analysis of the non-Newtonian behaviour of the medium.

Non-Newtonian Models

For Newtonian fluids, the shear stress is proportional to the strain rate $\left(\tau = \mu \dot{S}\right)$. Where μ is independent of $\dot{S}$. $\dot{S}$ is defined in general form as:

$$\dot{S} = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{1}$$

For non-Newtonian fluids, the viscosity becomes a function of $\dot{S}$, and is described by the variable η, where $\tau = [\eta(\dot{S})]\dot{S}$. Mathematical relations for $\eta(\dot{S})$ known as rheological models are abundant. In this paper modelling the fluid flow in dense medium cyclones in a laminar fashion and considering the Herschel-Bulkley and the Power Law models was carried out. The former is described by Equation (2). The Power Law results when the yield strain τo is neglected.

$$\tau = \tau_o + (k\dot{S}^{n-1})\dot{S} \tag{2}$$

In a three-dimensional model for cyclones, there are six components of the shear strain. Considering shear-dominated flow, the normal strains are neglected. Additionally, experimental measurements in hydro-cyclones have shown that the velocity gradient in the tangential direction for regions below the vortex finder is very small. So only the radial-axial strain (τ_{rx}) and axial-tangential strain($\tau_{x\theta}$) are significant. Then an axisymmetric approximation is justified for analysing the non-Newtonian effect of the fluid flow modelling.

Experimental Studies

It is widely reported that the magnetite medium is a non-Newtonian fluid. According to He (1994), the best rheological model was found to be the Casson model. Also, he found that the Herschel-Bulkley model also correlates well his experimental data, though he preferred the Casson model due to the physical significance of the Casson viscosity. Laskowsky (1994) conducted shear rate-shear strain measurements for different types of magnetite medium. Results for a medium of ultrafine magnetite is reported in Figure 2 and 3.

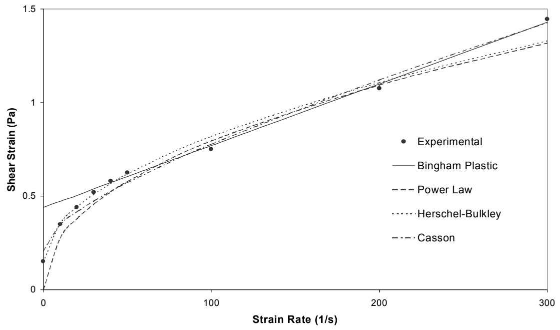

Figure 2: Curve fitting with different rheological models for shear strain vs strain rate experimental data of an ultrafine magnetite medium with 1.5 s.g.

According to Figure 2, in fact the Casson model represent best the ultrafine magnetite medium (r=0.995). Nevertheless, also the Herschell-Bulkley model correlates well the experimental data (r=0.985). With this model, for strain rate above 200 1/s, higher discrepancies are observed when the strain rate increases. A model with zero yield stress such as the Power Law model can also approximately fit the non-Newtonian data (r=0.980).

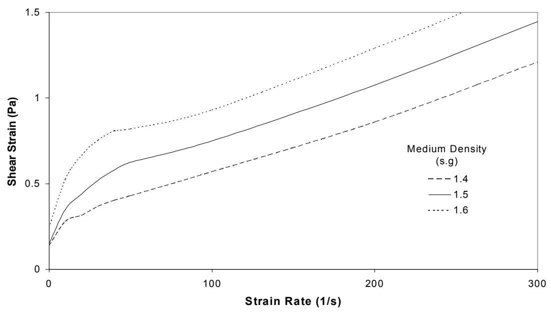

Figure 3: Shear strain vs strain rate measurements at different specific gravities.

If a Newtonian model is used to model the medium flow, then an equivalent Newtonian viscosity is required. This viscosity must be chosen to represent the whole range of the strain rate. Therefore, if a Bingham Plastic model is formulated and its yield stress neglected, the remaining equation gives the equivalent Newtonian viscosity. This viscosity is approximately constant at different densities according to Figure 3. Consequently, in the event of small segregation of magnetite particles in the medium, this viscosity can still be used.

Non-Newtonian Rheology and Turbulence Effect

Assuming axisymmetric geometry and considering the medium as a homogenous fluid, fluid flow calculations were carried out with two different rheological models. Additional calculations were performed for a Newtonian fluid for laminar and turbulent flows. The turbulent model is based on a Reynolds stress model (RSM) described below. Results in terms of axial and tangential velocity profiles at 106 mm and 270 mm form the cyclone roof are presented in Figures 4 and 5.

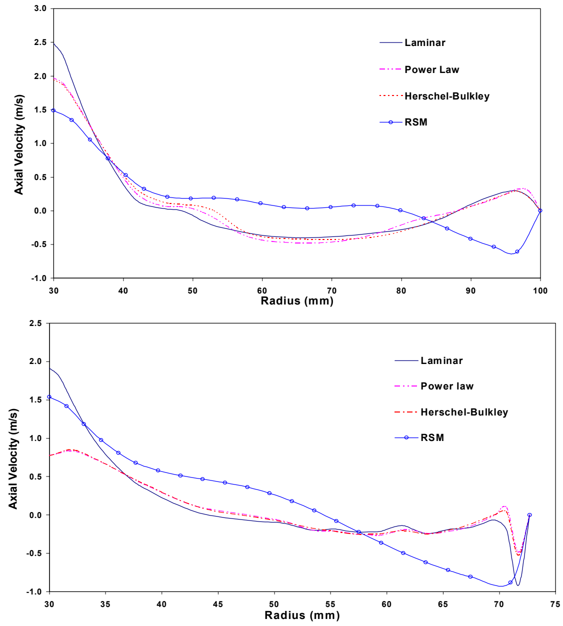

Figure 4: Effect of non-Newtonian models and turbulence on axial velocity profiles at 106 mm (top) and 270 mm from the cyclone roof.

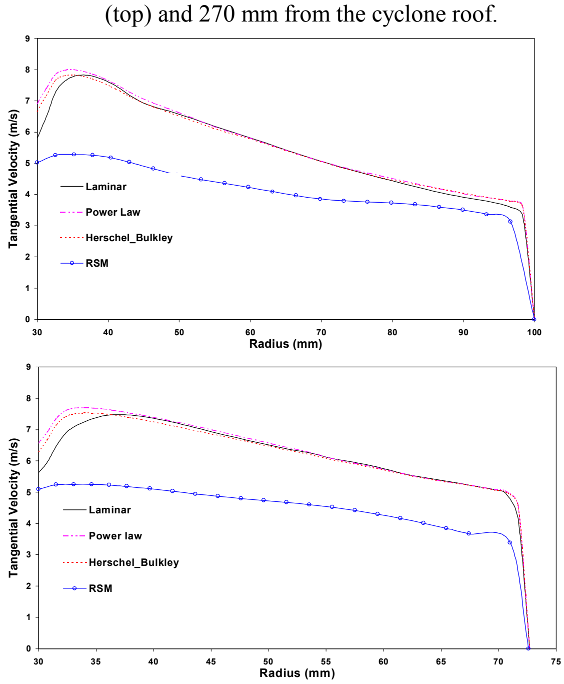

Figure 5: Effect of non-Newtonian models and turbulence on tangential velocity Profiles at 106 mm (top) 270 mm from the cyclone roof.

It can be noted that the axial and velocity profiles at the two locations for the non-Newtonian models and

Newtonian laminar are very similar. On the contrary, velocity profiles considering turbulence differ from the others. Therefore, turbulence appears to be more significant than the non-Newtonian rheology.

Consequently, if we consider the total viscosity for the fluid to be composed of the laminar, turbulent and non-Newtonian contributions, clearly the turbulence viscosity will be dominant, over-riding the influence of the others. So, a Newtonian turbulent fluid flow approximation for the dense medium behaviour is justified, provided that the turbulence is significant.

Some of the implications of this assumption in the coal separation process may be uncertain. For example, for the medium that follows the Herschel-Bulkley model, coal particles will need to overcome the yield strain to begin moving. This behaviour is expected in a laminar flow, however, in turbulent flows, the influence of the yield stress is unknown. Turbulence may also play a key role in suppressing the influence of the yield stress in the separation of coal particles.

A MODEL FOR DENSE MEDIUM CYCLONES

A model for dense medium cyclones is proposed. The model is an Eulerian-Lagrangian combination. The medium is considered a Newtonian homogenous turbulent fluid and is modelled in an Eulerian reference frame. A Reynolds stress model is used for turbulence modelling. Coal particles are modelled in a Lagrangian reference frame. Turbulence dispersion of the coal particles is considered with a stochastic model. The model is valid when the segregation effect of the magnetite particles is neglected and coal particles are present at dilute concentrations. This implies that the model is for dense medium cyclones operating at high densities and for high volumetric medium/coal ratio. This particular case is for a medium made of ultrafine magnetite particles dispersed in water with 1.6 s. g.

The implications of the segregation phenomena in the simplified model may be neglected considering that the model was built for a medium with ultrafine magnetite. Additionally, in practice higher viscosities of the medium are expected due to contamination of the medium by clay and other fine contaminants (Napier-Munn, 1990). Additionally, partition curves constructed by tracking coal particles in a Lagrangian reference frame may be equivalent to the one obtained experimentally by density tracer techniques when the dense medium cyclone is operating with only medium.

A Model for the Magnetite Medium Flow

The model is for a standard 350 mm DMC and can be easily extended to other sizes and geometries. In the medium modelling, the magnetite medium is assumed to be a homogenous Newtonian fluid. The air core diameter was estimated following the approach of Smith (1962) and its boundary treated as slip wall. A cylindrical mesh of 27x28x42 was used. Since the volumetric flow rate at the tangential inlet and the cross-section area are known, the tangential velocity is easily calculated. The apex flow rate is estimated with the algebraic expressions of Wood (1990). Then outlet conditions are applied to both the vortex flow and apex. For this type of boundary condition, the axial velocity is prescribed to be uniform with a value determined from the flow rate. Turbulent quantities are assumed and input as turbulence intensity (5%) and characteristic length (diameter of the inlet/exits). From these quantities, the kinetic energy and eddy dissipation rates at the inlet/exits are calculated. Near wall calculation was carried out with a standard wall function (Rodi, 1980). The near-wall values of the Reynolds stresses and ε are computed from this function

For the region far from the walls, the governing equations in their cylindrical form were solved. Due to limited space, only the continuity and momentum equations in their general form are presented here.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{3}$$

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu_l \frac{\partial u_i}{\partial x_j} - \rho \overline{u'_i u'_j}\right) + \rho g_i \tag{4}$$

where ρ is the density of the fluid, u_i is the mean velocity component in the i direction, u_i' the fluctuating component of the velocity, g_i is the gravitational acceleration and p is the static pressure, respectively.

For steady-state, the transport equation for the Reynolds stresses can be expressed in symbolic form as:

$$C_{ij} = P_{ij} + D_{ij} + \varphi_{ij} - \varepsilon_{ij} \tag{5}$$

where:

$C_{ij} = u_k \frac{\partial}{\partial x_k}\left(\overline{u'_i u'_j}\right)$ is the convective transport term,

$P_{ij} = -\left(\overline{u'_i u'_k}\frac{\partial u_j}{\partial x_k} + \overline{u'_j u'_k}\frac{\partial u_i}{\partial x_k}\right)$ is the production term,

$D_{ij} = -\frac{\partial}{\partial x_k}\left(\left(\overline{u'_i u'_j u'_k}\right) + \overline{\frac{p}{\rho}\left(\delta_{jk}u'_i + \delta_{ik}u'_j\right)} - \nu \frac{\partial}{\partial x_k}\left(\overline{u'_i u'_j}\right)\right)$ is the diffusion term,

$\varphi_{ij} = \overline{\frac{p}{\rho}\left(\frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i}\right)}$ is the pressure-strain term,

$\varepsilon_{ij} = 2\nu \overline{\frac{\partial u'_i}{\partial x_k}\frac{\partial u'_j}{\partial x_k}}$ is the dissipation term.

The Reynolds Stress turbulence model requires solving the six transport equations for the individual stresses $\overline{u'_i u'_j}$ plus a transport equation for the dissipation rate, which is similar to the transport equation for the dissipation rate in the standard k-ε model. The diffusion, the pressure-strain and dissipation terms are modelled. The detailed analysis and approximations of the several terms within the transport equations are described in more detail by Launder et al.(1975). Summarising, assuming isotropy of turbulence, the diffusion term is described using a scalar diffusion coefficient, the wall-reflection term is neglected and the dissipation term is assumed isotropic.

Calculations were carried out for the DMC inclined 15° with respect to the horizontal. A medium of 1.6 s.g density and 3.3 cp viscosity was used. Predicted axial and radial velocity vectors for a planes axially centred and perpendicular to the inlet are shown in Figure 6. From this figure it can be clearly seen the outer downward flow and the inner upward flow. The interaction of both flows generate the recirculation zones near the vortex finder region. The short-circuiting flow in the vortex region is also clearly shown.

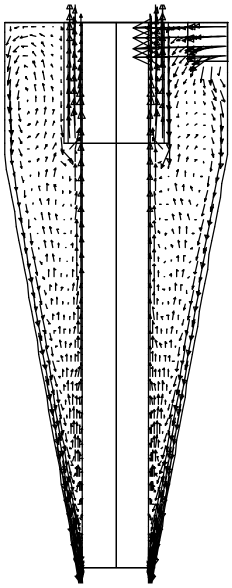

Figure 6: Axial and radial velocity vectors at perpendicular plane to the inlet in a standard 350 mm DMC.

A Model for the Raw Coal Particles Separation

Coal particles are modelled in a Lagrangian reference frame. The trajectory of an individual particle is predicted by integrating the force balance on the particle. For the i-direction in general coordinates, the equation is:

$$\frac{du_{pi}}{dt} = \frac{18\mu C_D \,\mathrm{Re}}{24\rho_p D_p^2}\left(u_i - u_{pi}\right) + g_i \frac{\rho_p - \rho}{\rho_p} + \frac{1}{2}\frac{\rho}{\rho_p}\frac{d}{dt}\left(u_i - u_{p_i}\right) + \frac{\rho}{\rho_p} u_{pi}\frac{\partial u_i}{\partial x_i} \qquad (6)$$

where the forces on the right-hand-side represent respectively the drag force, the gravity force, the virtual mass force, and pressure gradient force. The drag coefficient, C_D, is a function of the relative Reynolds number of the following general form:

$$C_D = a_1 + \frac{a_2}{\mathrm{Re}} + \frac{a_3}{\mathrm{Re}^2} \qquad (7)$$

where the constants are given by Morsi and Alexander (1972). Equation (6) is linearised and a variable time step Runga-Kutta technique for integration of the particle equation of motion is used. This procedure selects the integration time step based on the residence time of the particle within each medium control volume. The maximum time steps was fixed to be 20,000.

To predict the dispersion of the particles due to turbulence, the fluctuating medium velocity components are obtained by solution of the Langevin equation (Thomson, 1987), generalised for 3-dimensional flow as:

$$du_i = \frac{1}{T}u_i dt + \left(\frac{2\overline{u_i' u_i'}}{T}\right)^{1/2} dw \qquad (8)$$

where w is a Gaussian distributed random number and T is the integral time. T is approximated as $T_L \approx 0.30k/\varepsilon$, where T_L is the medium Lagrangian integral time. In order to improve the accuracy, the maximum time step is limited to be less than *0.3 T*. The trajectory of each particle is computed *10* times. Finally under the assumption of dilute concentrations for coal particles only one-way coupling is considered.

Results in terms of partition curves for two coal particle sizes are shown in Figure 7. Degradation of the separation efficiency for finer coal particles can be seen. Also, the density of separation for finer particles is higher. Finally the displacement of the particles (coal and waste) in the undesired stream are more evident when fine particles are treated.

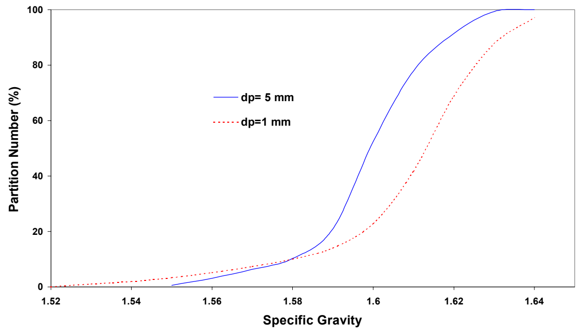

Figure 7: Partition curves for 5mm and 1mm coal particles in a 350 mm DMC.

Trajectories of 5 mm diameter coal particles at different densities are also shown in Figure 8. Their residence time is also reported in Table 1. For comparison purposes in all the cases, the particle is injected in the centroid of the square at the beginning of the inlet. From this information it can be concluded that the coal particle of low density is initially affected by the recirculation zone while the high density coal is not effected at all. The former tends to be trapped in the cyclone roof; however, as soon it reaches the vortex finder wall, it is dragged out by the short-circuit flow. The neutrally-buoyant particle is initially dragged down by the external downward flow. At the same time, the radial velocity pointing to the air core causes the particle to be dragged inwards. Consequently, in some part of the conical section, the particle is caught by the upward inner flow to be reported at the overflow. The neutrally-buoyant particle is shown to be very unstable and it needs a larger residence time than the others for its trajectory to be established.

Case	ρ s.g.	t sec
1	1.55	3.7
2	1.60	5.8
3	1.65	2.3

Table 1: Residence time for 5 mm coal particles of different densities.

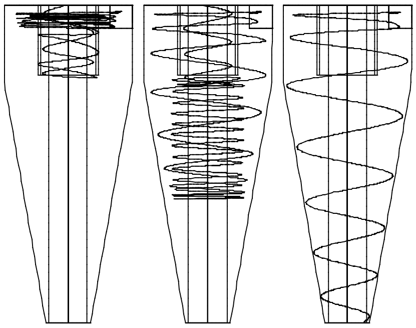

Figure 8: 5 mm diameter coal particles trajectory of different densities: 1.55 s.g. (left), 1.60 s.g. (middle) and 1.65 s.g. (right).

CONCLUSION

The effect of the non-Newtonian rheology of the medium and turbulence phenomenon in the modelling process was analysed. It was found that the turbulence effect dominate the influence of the non-Newtonian rheology. Then, a model was constructed for the medium for a particular case where the segregation for magnetite can be neglected. Also a model for the coal particles at dilute concentrations was presented. As a result a model for DMCs was proposed. The model is a combination of an Eulerian model for the medium and a Lagrangian approach for the coal particles. Finally given the framework for future developments, a more comprehensive model is being devised.

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