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TWO WAY COUPLED CFD-DEM MODEL TO PREDICT TUMBLING MILL DYNAMICS

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ABSTRACT

The high energy inefficiency of tumbling mills has been the focus of much of modern day comminution research, Harsh milling conditions limit experimental measurement so the mill designers have to rely on empirical relations. The scope of the present work is to prepare a computational model that can accurately predict the complex multiphase dynamics of charge, air and slurry inside the mill using a coupling between computational fluid dynamics and discrete element method. The slurry air system is modelled using Volume of fluid (VOF) method and the charge motion is modelled by discrete element method. The phases are coupled using the interphase momentum exchange between the charge and the fluids at each fluid flow time step. The coupled model is compared with experimental results from the positron emitting particle tracking (PEPT) camera. The results show good qualitative agreement with equivalent PEPT findings. It is observed that out of the four modelling approaches investigated the Two-way coupled model gives the best agreement with the PEPT findings. The model can be useful in better understanding of the mill dynamics which can lead to more efficient design.

NOMENCLATURE

m	mass of particle
v	velocity of the particle
F_{ti}	contact force
F_{fp}	Force on particle p by the fluid
g	acceleration due to gravity
ω	angular velocity
q	damping coefficient
k	spring constant
x	deformation of the particle
ε_f	fluid volume fraction
ρ_f	density of the fluid
u_f	fluid velocity
p	pressure
τ_f	shear stress acting on the fluid
μ	dynamic viscosity
ε_s	solid volume fraction

INTRODUCTION

Tumbling mills are extensively used comminution equipment in the mineral industries even though they are highly energy inefficient. According to a survey of copper production presented by Schroenert (1986), milling accounts for roughly 60 percent of the total energy input. Out of which the amount of energy needed for fracture is only a small fraction around 1-5 percent (Lowrison 1974).

The slurry formed by the mixing of the feed water and the fine ore particles is very important for the material transport to the grinding zone, subjecting the materials to grinding action and transport of fine ore through the discharge. Any parameter affecting these processes will affect the grinding efficiency. The probability of overall breakage is the product of the probability of capture and the probability of breakage upon capture (El-Shall and Somasundaran 1984). Therefore effective knowledge of slurry dynamics can be very useful for modelling the charge motion of these mills and for the design of mills with increased probability of particles being captured in the grinding zone.

The work presented in this article is to prepare a computational model that can accurately predict the complex multiphase dynamics of charge, air and slurry inside the mill using a coupled model between Volume of fluid and discrete element method. The slurry air system is modelled using VOF method and the charge motion is modelled by discrete element method. Two coupling approaches are investigated. In the first, the so called one way coupling the phases are coupled using the inter phase momentum exchange between the charge and the fluids at each time step by resolving the forces from DEM on per cell basis and adding it as the source terms to the fluid cells. The second is a two way coupled approach in which subsequent calculation of the drag force on the particles using fluid field data is also done to account for the effects of slurry dynamics on the charge motion. The coupling is implemented using C++ subroutines and the source terms are calculated using Fluent UDF, the drag force on the particles are updated as particle body force using EDEM application programming interface. The coupled model is validated against experimental results from the positron emitting particle tracking (PEPT) camera. Matlab subroutines are developed for visualizing time averaged and axially averaged solution for comparison with the PEPT results.

MODEL DESCRIPTION

Discrete Element Modelling of Charge Particles

The solid particles are discrete spherical bodies which interact with other particles at point of contact only. Therefore, a continuum approach cannot be used to model such cases. The Discrete element method pioneered by Cundall and Strack (1979) is the numerical scheme used for simulating the system of discrete interacting bodies. The position of each particle is tracked and the force acting on it is updated when contact between the bodies or other geometry takes place. The discrete element method calculates normal and tangential velocities using the Newton's law of motion.

$$m\frac{dv}{dt} = F_{ti} + F_{fp} + m_i g$$

$$m\,\frac{d\omega}{dt} = I$$

A non-linear hertzian model is used in the present work which calculates the contact force due to overlap between two particles using the soft sphere approach same way as that of the spring dashpot model but the difference is that instead of the force being a linear function of deformation and deformation rate it is a polynomial function. The damping coefficient used in the spring dashpot model is also a function of thee deformation as well as the rate of deformation. The force calculated for deformation x using the hertzian model is given by the following equation.

$$F_{ti} = -qx^{0.25}\frac{dx}{dt} + kx^{1.5}$$

The forces calculated due to contact once is used to calculate the velocity and position for the next time step using a leap frog time stepping scheme and Newton's law of motion for the calculation of acceleration and subsequent velocity calculation during that time step followed by updating the particle position.

Initial simulation was done to validate the discrete element method to accurately predict the charge motion inside a tumbling mill. Set of dry DEM simulations were conducted varying the fill level and the speed of the mill. The particles were modelled as spherical balls of diameter 5 mm. The contact between the particles as well as between particles and mill walls are modelled by nonlinear hertzian model. The Rayleigh time step calculated based on the above material properties was 0.00000337 sec. The time step size for the simulation was chosen to be 0.000001 sec. A total of around 50000 particles were initialized position by filling a cylindrical section centred at origin, having radius 0.125 cm and length of 0.25 cm corresponding to 31.25 % mill loading. Each particle was assigned to zero velocity initially. Mill load is varied by varying the volume of the cylinder containing the particles. The same case setup as that of the pure DEM simulation is also used for the two way coupled model the difference being an added force that is because of the fluid coupling. The commercial code EDEM 2.4 was used to solve the particle motion equations. The non-linear hertzian model inbuilt in EDEM was used to model the contact forces. For the two way coupled model, the drag force on the particle due to the fluid flow is calculated and added to the total force acting on the particle using the application programming interface platform of EDEM.

VOF Modelling of Slurry-Air Multiphase Flow

The governing equation for the multiphase flow of incompressible fluid is the equation of continuity and the Navier-Stokes Equation

$$\frac{\partial \varepsilon_f \rho_f}{\partial t} + \nabla \varepsilon_f \rho_f u_f = 0$$

$$\frac{\partial \varepsilon_f \rho_f u_f}{\partial t} + \nabla \varepsilon_f \rho_f u_f u_f = -\nabla p + \nabla \tau_f + \varepsilon_f \rho_f g + F_{fp}$$

In case of a Newtonian fluid we can replace $\nabla \tau_f = \mu \nabla^2 u_f$.

To account for the effect of the drag force from the solids on the fluid we need from the DEM simulations the solid fraction ε_s as well as the solid field velocity u_s.The calculation of the drag force in the present work is done using Beetstra(2005) in the current work. The slurry-air multiphase system was modelled using the volume of fluid model inbuilt in Fluent 13.0. The turbulence was resolved using inbuilt Realizable k-epsilon model. Phase coupled SIMPLE algorithm was used for pressure velocity coupling and second order upwind scheme is used for spatial discretization. The volume of fluid model is a single fluid model extensively used for liquid-gases stratified or free surface multiphase flows. To model two or more immiscible phases VOF solves only a single set of continuity and momentum equations and tracks the volume fraction of all the phases throughout the domain. Volume of each phase is tracked and the shapes of the interface between the phases are represented by interpolation schemes. The viscous properties of the slurry were matched to those for the PEPT experiments. The surface tension of the slurry was taken to be the same as that of water, which is 0.07 N/m. This is in agreement with surface tensions for a variety of mineral slurries measured by Baldyga et al. (2008), which were in the range 0.0669-0.0747 N/m. The density of the slurry is increased according to the percentage of solids in the slurry.

Coupling Implementation

The larger size particles in the mill are modelled by the discrete element method, and the slurry air system is modelled using VOF method. In the dense particle flow regime drag force is the predominant force that is the cause of momentum exchange between the phases. In one way coupling the porosity and the velocity fields from DEM simulations is averaged over 0.0001 seconds and resolved on per cell basis to calculate the drag force to be added as the source term as given in the governing equation for the fluid to (Malahe 2011). In the two way coupling he mean fluid velocity field from slurry air multiphase flow is interpolated to the particle centre to calculate the relative velocity between the phases, which is used to calculate drag on the particles. The correct implementation of the coupling between the discrete and continuous phase the flow variables must be constant over time at least within some statistical bounds. For this to be the case, the force applied by the particles on the fluid should also be steady, which requires the same of the velocity of the particles and the local averaged solidicity, since the particles are in motion, this will never hold for a given point in the charge, and can only be true over some averaging volume and time. The averaging time interval depends on the relaxation time for the slurry, work by Blakey and James (2003) show that laterite slurries having solids concentration less than 9% show almost instantaneous relaxation times. The slurry phase used in the current work have solid concentration above 20% solids, therefore for the current work the averaging of the forces is done at an interval of 0.0001 sec for slurry. The volume averaging is done by distributing the mass of the particle throughout its volume and then averaging the contribution in each CFD cells using the method of sample points as shown in figure 1. Each particle is represented by a fixed number of sample points each having the same volume fraction and the contribution of each sample points in each cell of the given eulerian mesh.

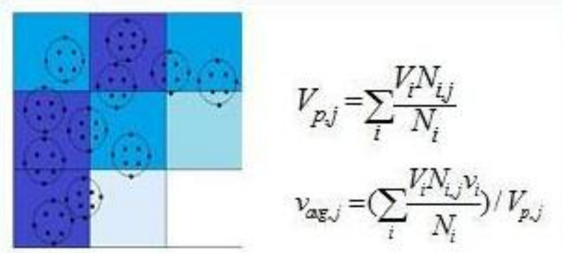

Figure 1: Particle discretization on the eulerian mesh

The fluid data at the end of each time step is passed to the coupling interface where it calculates the force on the DEM particles for the next set of time-steps by interpolating the flow quantities on the centre of the particle using a Kernel function (Zhao and Shan 2013). The fluid flow time step is fixed to hundred times the particle time step. The most accurate implementation of coupling requires the data exchange at the end of each time step, but since the computation of forces for each time step is computationally very demanding and the relaxation time of the slurries is of the range of the fluid flow time steps the exchange of data at an interval of the fluid flow time step seems a reasonable trade off.

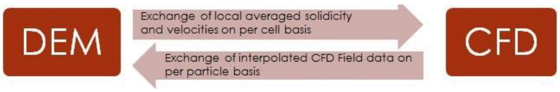

Figure 2: Two way coupling algorithm

RESULTS

The mill dynamics was studied using 4 models namely

1. DEM Model
2. VOF Model
3. One way coupled model
4. Two way coupled model

The DEM model is used to simulate the charge motion inside the mill. The VOF model is used to simulate the slurry air free surface profile. The one way coupled model uses the DEM data to simulate the slurry air system by incorporating the effects of charge motion. The charge profile is same as that of the pure DEM approach. The effects of slurry dynamics on charge and vice versa is reported using the two way coupled model.

Simulations were performed using the EDEM 2.4 and Fluent 13.0. Density and viscosity of the slurry is 1280 Kg/m3 and 0.0012 cp respectively. The particles are mono sized having diameter 5mm and density 2200 Kg/m3. The exchange of coupling force takes place at each 100 DEM time step which is equal to 1 time step of the VOF solver. All the simulations are run for time corresponding to 5 mill rotations which was 6.5 seconds of real time simulation.

Parameters	Pure DEM	Pure CFD	One way coupled	Two way Coupled
Particle number	51920	n/a	51920	51920
Particle density(Kg/m3)	2200	n/a	2200	2200
Particle-wall static friction	0. 306	n/a	0.306	0.306
Particle-Particle static friction	0.52	n/a	0.52	0.52
Restitution coefficient	0.8	n/a	0.8	0.8
Slurry density(Kg/m3)	n/a	1280	1280	1280
Slurry viscosity(cp)	n/a	0.0012	0.0012	0.0012
Mill diameter(m)	0.3	0.3	0.3	0.3
Mill length(m)	0.335	0.335	0.335	0.335
Mill rotation speed (rad/s)	4.852	4.852	4.852	4.852
Surface tension	n/a	0.07	0.07	0.07

Table 1: Parameters for the four models.

Validation and grid check

To find out whether the solution obtained has grid dependency the two way coupled simulation results were obtained for 3 different mesh sizes having 100000, 150000 and 200000 cells respectively. The tangential velocity plot was compared for different mesh size as given in figure 3, it was observed that the solution in case of mesh size having 150000 and 200000 shows slight difference. Therefore in order to reduce the computational cost the mesh size having 150000 cells is used.

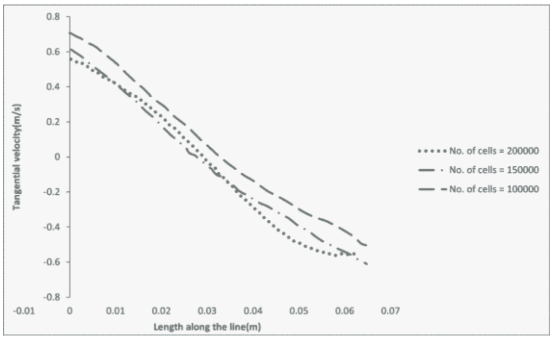

Figure 3: Grid Independence test for three different mesh sizes

The tangential velocity plot along a line passing through the diameter and the centre of mass of the mill from the PEPT experiment (Govender et.al. 2011) was compared to the tangential velocity plot obtained from the different model was compared in figure 4. Since the axial centre of mass profile is not constant an average value of the centre of mass is considered for the time-averaged solution of all the four models. Comparison shows the tangential velocity of the particles calculated by the dry DEM model over predicts the experimental results this is due to the fact that the dry DEM model does not account for the shear damping caused due to the slurry. The profile obtained from the DEM and one way coupled model show the same trend as the experimental findings, though near the free surface of the charge which in the graph is a region near the far length of the line (0.06-0.08m) it is observed that the values are over predicted which is due to the undamped motion of the particles without the slurry shearing effects. The two way coupled model shows the most reasonable agreement with the experimentally found values as the two way coupled model accounts for the drag on the slurry as well as the shear damping effects of the slurry on the particles it is the most accurate modelling approach between the phases among the four models in this study.

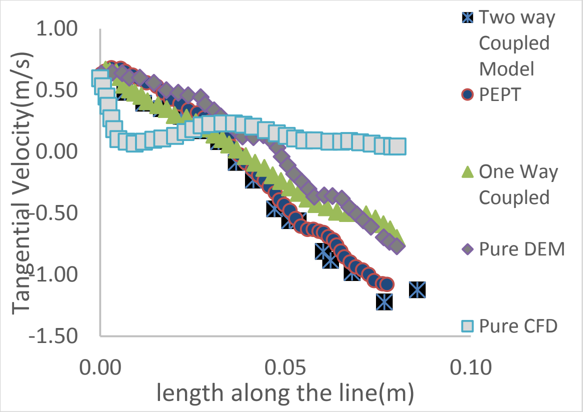

Figure 4: Comparison of tangential velocity along the line joining centre of circulation to the centre of mill for the studied models and PEPT experimental results.

Solidicity Comparison

The time averaged results are presented in the figures given below the comparison between the PEPT and the coupled model is presented in figure 5 for mill loading of 31.25\% by volume and 60% critical speed corresponding to a rotational velocity of 4.852 rad/sec and equivalent PEPT experimental results. The qualitative comparison show that the coupled model show good agreement with the experimental results as far as the solidicity is concerned but the major region of difference between the dry DEM and the experimental result is the free surface profile of the charge this is due to the fact that the motion of the particles in the mill is damped by the presence of slurry due to the retarding drag force from the slower moving slurry. The dry DEM model does not account for the slurry motion effects on the particles therefore increased cataracting of particles and free surface profile is not as smooth as the experimental findings. The solidicity profile obtained from one way coupling is the same as the dry DEM case as the effects of slurry motion on the larger size particles are not accounted. The two way coupled model which accounts for the effects of slurry gives a better comparison with the experimental findings with the free surface profile being smoothed similar to the experiment.

Transverse Volume Fraction Comparison

Figure 6 shows the axially-averaged and time-averaged flow quantities for slurry only with 30% solids concentration by mass and no coupling in the 30 cm mill rotating at 60% critical speed. The difference in the results from the pure CFD model and the PEPT results is due to the fact that the effects of drag from the solids on the slurry have a profound effect of slurry dynamics and transport inside the mill. The free surface profile obtained from the time averaged and space averaged solution is compared with the equivalent profile obtained from PEPT experiments. The comparison of free surface profiles of the slurry inside the mill using the one way coupled and the two way coupled model with the equivalent PEPT findings shows that due to the solid motion the slurry is also lifted because of the drag and the recirculates around the centre of circulation. The free surface profile from both the coupled models shows slight variation particularly at the shoulder and toe region. Possible reasons being the over prediction of drag forces in the one way coupled model caused due to undamped motion of the particles as obtained from the pure DEM simulations.

CONCLUSION

The complex three phase flow can be modelled efficiently using coupled DEM-CFD model. The pure DEM model can effectively predict the particle flow but it generally over predicts as the effect of shear forces from the slurry which tends to damp the motion of the particles is not considered. The pure CFD model fails to predict the free surface profile of the slurry air system inside the mill but the one way coupled model can effectively predict the free surface, so we infer that there is a major effect of drag forces of particle on the fluid. Once the drag force from the DEM simulation is incorporated as momentum source terms in the fluid cells the slurry free surface profile from the coupled model gives a better comparison with the equivalent PEPT experimental results. The major difference in the comparison with PEPT finding is the region near the centre of circulation of the mill, this is due to the fact that slurry is modelled as continuum fluid rather than discrete 1mm particles as in the case of PEPT slurry experiments. The effect of slurry on the solid is also examined using the two way coupled model and the damping of the solid motion is observed as evident from the contour plot of the charge profile which shows less cataracting of particles and a smooth free surface profile which was absent in the case of dry DEM case. Comparison with the experimental data show that the coupled DEM-CFD model shows better agreement compared to the dry DEM case. As in the case of slurry fraction is concerned both the one way and two way coupled model show similar profiles except for the shoulder and the toe region this is due to the fact that drag force calculated in one way coupled will always be greater than the one calculated by a two way coupling approach as in the latter case the particle velocities are slightly reduced due to the slurry shearing action. The quantitative comparison of the tangential plot shows the dry DEM, one way coupled and two way coupled model show the reasonable agreement with the tangential velocity profile of the experiment. The two way coupling least difference with the experimental findings, as the tangential velocity profiles near the free surface of the charge calculated by the DEM and one way coupled model over predicting the value as can be observed at the far end of the line length which is the region near the free surface. Future work will be focussed on studying the effects of slurry rheology on the charge particles motion and implementation of parallel coupling algorithm to speed up the calculation.

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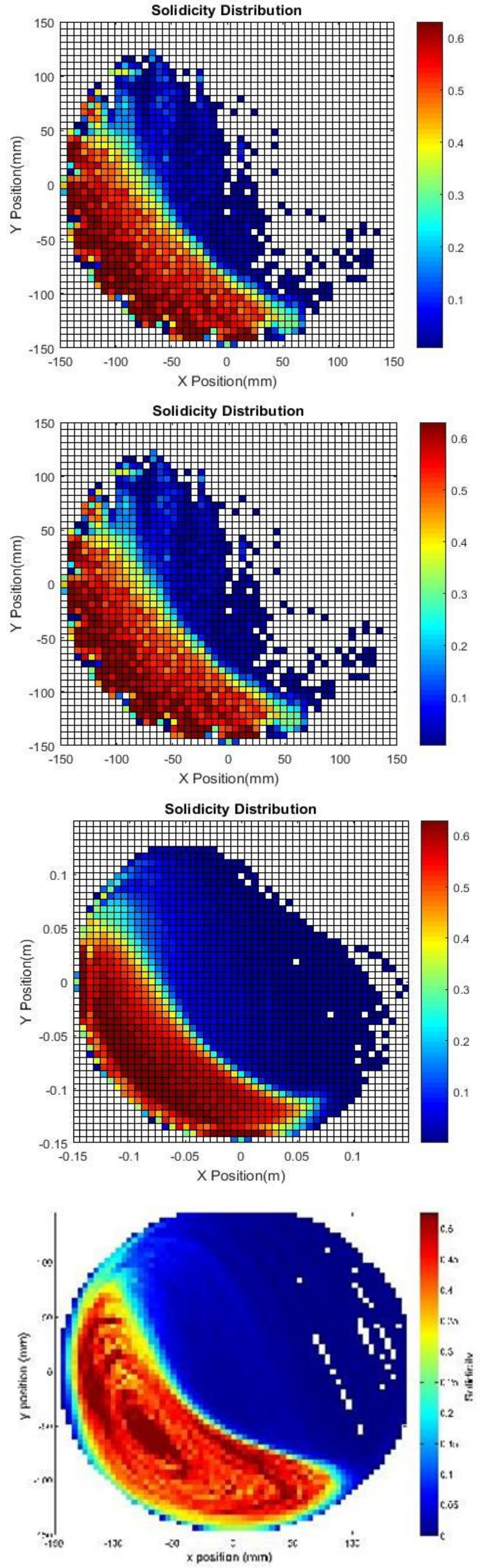

Figure 5: Transverse solidicity comparison. From Top: Pure DEM, One way coupled model, Two way coupled model Bottom: PEPT results.

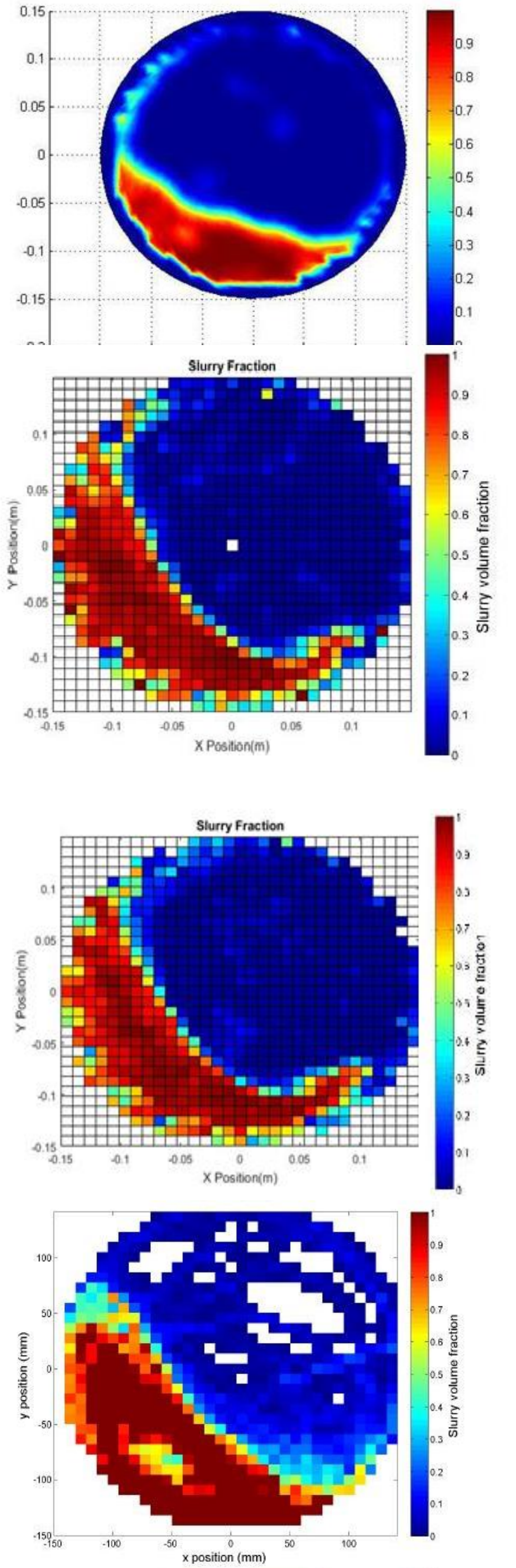

Figure 6: Transverse slurry volume fraction comparison. From top: Pure CFD, One way Coupled Model, Two way Coupled Model, PEPT results.

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