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SLURRY FLOW IN A TOWER MILL

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ABSTRACT

Tower mills are a commonly used device for fine grinding in the mineral processing industry and can be used for dry or wet grinding applications. In wet grinding, the nature of the slurry flow plays an important role in transporting feed rock and ground fines inside the mill and also assists discharge from the mill. Operating conditions and impeller design can affect the slurry distribution within the mill with some regions of the charge potentially being drier and others saturated. To help understand the slurry distribution and transport we use a two stage modelling process. The Discrete Element Method (DEM) is used to characterise the motion and distribution of the grinding media in the tower mill. The averaged voidage distribution and steady velocity field from the DEM model is then used to define a dynamic porous media in the fluid model. The Smoothed Particle Hydrodynamics (SPH) method is used for modelling the fluid flow because of the free surface and the moving impeller. The one way coupled DEM/SPH model is then used to assess how the fluid distribution and flow pattern of the slurry in a tower mill are to variations in the slurry viscosity.

INTRODUCTION

Understanding slurry transport in wet grinding applications is important for optimising the performance of such devices. Moys (1989) identified slurry viscosity as the most important control parameter for grinding mills. However, there is conflicting evidence in the literature for viscosity effects on mill performance since the effects are very sensitive to slurry rheology (Shi & Napier-Munn, 2002). The effect of viscosity on grinding efficiency has been shown to depend on whether the slurry has high (Klimpel, 1982) or low yield stress (Gao & Fossberg, 1993). The viscosity will likely influence transport and comminution in the mill. High viscosities will tend to slow the media, but can also aid capture of feed particles between balls. At low viscosities, the fluid phase will lubricate the media reducing grinding efficiency as enabling the transport of fines out of the mill.

Slurry density may also affect mill performance as there is some expectation that it will influence the distribution of impact energies. Bazin & Obiang (2007) showed that slurry density may also need to be well matched to the feed size distribution. Low slurry densities resulted in a better grind for coarser feeds, whereas high densities were found to be preferable for fine grinding.

Despite much experimental work on slurries at the lab-scale, no conclusive understanding yet exists for how slurries influence grinding performance at industrial scales and particularly in the case of high solids loading. When the solids concentration is substantial, slurries exhibit Non-Newtonian behaviour. At high slurry densities and low fines concentration slurries show pseudoplastic behaviour, but at low density and high fines they exhibit dilatant behaviour. A review of various characteristics of slurry rheology for wet grinding applications is given in He et al. (2004). They suggest that optimization of slurry rheology for a mill may provide increased throughput, energy efficiency, and fineness of product.

Tower mills consist of a stationary, cylindrical grinding chamber filled with grinding media (such as steel or ceramic balls). They use a rotating screw agitator which generates a strong recirculation within the mill as media is conveyed upwards inside the flights of the screw and flows downwards outside the screw. The tower mill has been shown to have excellent transport properties and to maintain very good media participation rates throughout a large fraction of the grinding chamber volume suggesting a significant increase in grinding performance over pin mills (Sinnott et al. 2006; Cleary et al. 2006b). Most of the grinding in tower mills is thought to occur within a high shear, annular zone located between the outer edges of the rotating screw and the stationary mill shell. The breakage mechanism in tower mills is different to that of tumbling mills. It involves the shearing of fine particles between adjacent layers of media with high differential shear and high pressures.

Over the last two decades, DEM has been used extensively for modelling different types of grinding devices. Mishra and Rajamani (1992) performed the earliest DEM simulations of ball mills. Axial transport and grate discharge were studied by Cleary (2006). Many DEM studies of SAG mills have also been undertaken (Rajamani and Mishra, 1996; Herbst and Nordell, 2001; Djordjevic et al., 2006). A recent overview of DEM models for grinding processes is summarized in Cleary et al. (2008). In contrast to tumbling mills, models for understanding the basic concepts of fine grinding have not yet matured. Additionally, very few models have been attempted for studying wet-grinding applications with Cleary et al. (2006a) and Jayusandra et al. (2009) being the most notable examples.

The aim of this paper is to use a two stage modelling process to describe the fluid and solid phases of the slurry and charge. A DEM model is used to describe the motion and distribution of the grinding media in the mill and SPH model is used for the fluid phase. A one way coupled DEM/SPH model is then used to assess how the fluid distribution and flow pattern of the slurry in a tower mill depends on the slurry viscosity.

MODEL DESCRIPTION

Approach to the DEM-SPH Coupled Slurry Model

The problem of slurry transport and its role in wet-grinding requires the ability to model the particulate solids in the charge and the slurry. To do this, we couple two different computational methods to model the particulates and slurry separately. DEM is used to model the grinding media in the tower mill, and SPH is used to model the fluid slurry. The methodology used here for the coupled DEM particulate / SPH slurry model follows that proposed by Cleary et al. (2006a). With this approach we:

1. Perform a 3D DEM simulation to predict the flow of the media in the tower mill. The flow data is then averaged onto a cylindrical grid to obtain steady-state volume fraction and velocity distributions that characterise the charge as a dynamic porous media.
2. This continuum representation of the porosity and velocity information of the solid particulates is then supplied to the SPH software.
3. Perform a 3D SPH simulation to predict the flow of slurry through the porous charge using a specified slurry viscosity. A Darcy drag force is applied to the fluid based on the porosity and velocity distributions in the charge.

This one-way coupling of the solid particulates and the slurry is possible because in the rotating frame of the screw, the media flow is in steady state. We assume that the media velocities are only weakly affected by the slurry motion which is reasonable given its densely packed state and its being made up of heavy steel balls. The slurry motion should therefore be dominated by the flow of the media. At very high slurry viscosities this may not be true.

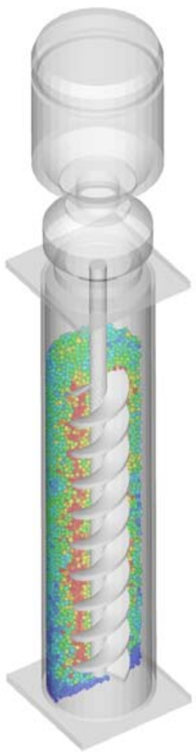

Figure 1: The pilot-scale tower mill geometry used for the DEM and SPH simulations. It is shown filled with ceramic media coloured by flow velocity.

DEM: Dynamic Porous Media

DEM is a computational technique that allows particle flows in various types of equipment to be simulated. It involves following the motion of every particle (coarser than some cut-off size) in the flow and modelling each collision between the particles and their environment, such as the mill liner or screw agitator. This has the advantage of being able to simulate equipment under very controlled conditions and to be able to make detailed predictions of specific outputs while providing insight into the flow patterns and breakage processes. The general DEM methodology and its variants are well established and are described in review articles by Campbell (1990), Barker (1994) and Walton (1994). Here we use a conventional linear-spring and dashpot variant of DEM which is described in detail in Cleary (2004).

A DEM simulation of media flow in a pilot-scale tower mill was performed to characterise the dynamic porous media for the slurry simulations. The mill is shown in Figure 1 and employs a double helical, steel screw agitator inside a cylindrical grinding chamber. The role of the screw is to stir the media while simultaneously lifting and circulating it throughout the mill. The dimensions for the pilot-scale mill are summarised in Table 1. The mill chamber was filled with dry, spherical ceramic media with sizes distributed uniformly in a range -9 + 14 mm (as shown in Figure 2). A specific gravity of 2.7 was assumed for ceramic media. The total media mass in the mill was 58.4 kg for 29,900 particles. A coefficient of restitution of 0.3 and a friction coefficient of 0.5 were used for media–media and media–boundary collisions.

Rated Power	1.5 kW
Angular Speed	100 rpm
Chamber Volume	39 L
Stirrer	Double Helical Steel Screw
Chamber Diameter	0.24 m
Chamber Height	1.2 m
Stirrer Diameter	0.14 m
Stirrer Shaft Diameter	0.04 m
Pitch	0.09 m

Table 1: Specification of the pilot-scale tower mill as used for the DEM simulations.

Grinding media were modelled with the assumption of no breakage or attrition of the media particles over the short duration of the simulations. Feed powder material was neglected since this is typically below 100 μm and is not directly resolvable with DEM in mill scale simulations. The absence of feed particles was not expected to significantly affect the media behaviour (because of the dominant masses of media particles). A spring constant of 50,000 N/m was chosen for the simulations to give average particle overlaps of about 0.5% for all cases.

The simulation was monitored until the power draw for the screw was steady. A cylindrical grid was then superimposed over the mill and constrained to rotate with the screw. Particle velocities and positions were averaged on this grid to determine the properties of a continuum porous media representation of the charge.

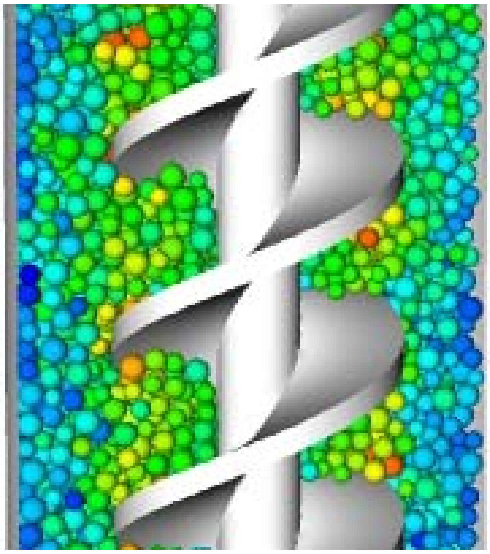

Figure 2: 3D flow of DEM grinding media inside the mill chamber and coloured by speed.

Figure 3 shows the averaged solid fraction and flow velocities of the DEM porous media representing the charge. Figure 3a shows how the media packs inside the mill chamber. The top layers of the charge are well above the top of the screw. The annular red region against the wall, shows that media is densely packed at close to the packing limit of 0.6 for spheres. Near the screw the packing reduces to about 0.45-0.55 in an annular region adjacent to the screw edge. This mildly dilated region corresponds to the mill's grinding zone described in Sinnott et al. (2006). Packing declines further to about 0.4 just below the screw blade as it is hard for balls to reach this location.

Figure 3b shows radially directed flow in the mill. At the base of the mill there is a strong flow inwards at the start of the screw. At the top of the mill there is strong flow radially outwards as media are pushed outward by the screw towards the walls. For each screw flight there is also a small concentrated flow outwards from the top of the blade edge and inwards underneath the blade. This suggests a local recirculation around the spiral edge of the screw flight.

Figures 3c&d demonstrate the characteristic media recirculation of the tower mill. The screw imparts a strong swirling motion to the media as shown by the high tangential velocities near the screw in Figure 3c. The velocities reduce near the wall due to frictional interaction with the stationary shell. Figure 3d shows the strong axial circulation generated by the strong transport attributes of the screw. Media are conveyed steadily upwards by the screw (red region) and then flow back down near the mill shell (blue region).

SPH Slurry Flow Simulation

SPH modelling of free surface fluid flows is well established (see Cleary and Prakash, 2004; Cleary et al., 2006c). The SPH method is described in detail by Cleary et al. (2007). A broad range of applications of SPH to industrial flow processes are given in its references. Conventional SPH is a particle based method for solving the Navier–Stokes equations with free surfaces in complex moving geometries (such as around the screw agitator) and is ideally suited to modelling fluid flow in grinding mills.

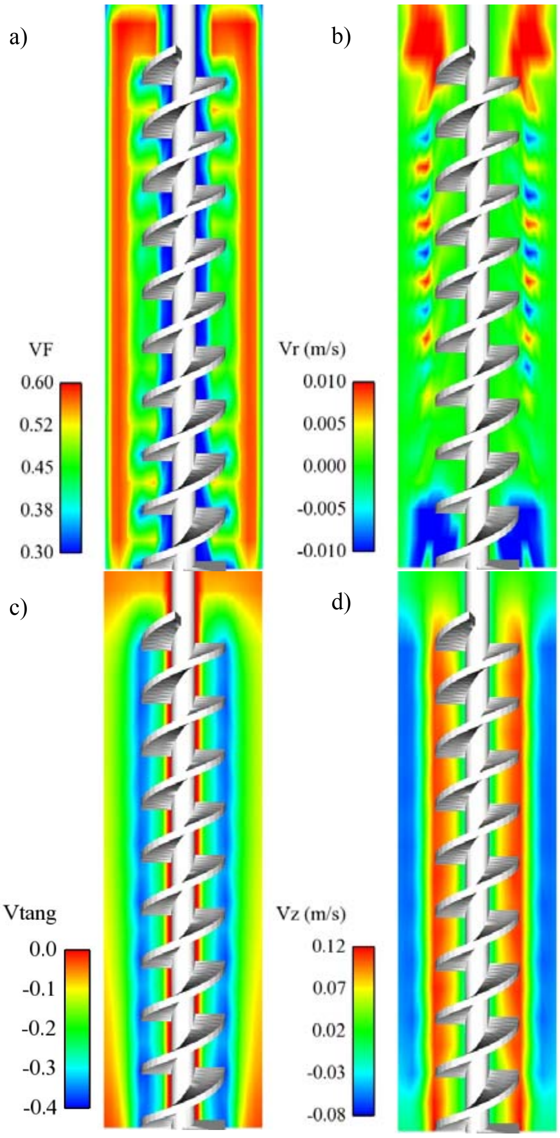

Figure 3: Steady-state distributions of: a) solids fraction; b) radial, c) tangential and c) axial velocities for DEM grinding media in the tower mill

SPH simulations were performed to predict the slurry flow driven by both the screw and the motion of media (represented here as a dynamic porous media with properties given by the distributions shown in Figure 3). The fluid rheology was assumed to be Newtonian for the purpose of this initial study. A Darcy drag force for the fluid was defined based on the DEM derived porosity and velocity distributions (see Cleary et al. 2006a for details). The Kozeny-Carman relationship was used to predict the permeability of the media based on the charge properties. For the ball size distribution in the mill the surface area per unit volume of porous media is 530. The tortuosity used was 2.0 and the shape factor for spheres is 2.5. The highest solid fraction found in the mill was 0.604. This corresponds to a permeability of 1.24×10^{-7}. This is almost two orders of magnitude less permeable than the charge in the previously investigated SAG mill (Cleary et al 2006a).

The boundary geometries for the stationary mill and rotating screw were used to create SPH compatible forms based on boundary particles. The screw motion was imposed on these particles. The boundary particle separation used for the discretisation of the objects was 6.5 mm resulting in about 50,000 particles. A fluid particle resolution of 5.9 mm was used. The mill was filled with fluid to a level just above the top of the ball charge so there is a small pool of liquid with a free surface at the top. This volume consisted of around 74,000 particles. Feed and discharge of slurry from either the top or bottom of the mill (depending on specific designs) can easily be included. For simplicity, these are ignored and the slurry is allowed to recirculate at steady state.

A slurry density of 1000 kg/m^3 was used. Viscosities of 0.01 and 0.1 Pa.s were used as they span much of the practical viscosity range found in tower mills. A speed of sound of 12 m/s was sufficient to maintain the density variation level (0.5-1.0%) required for incompressibility. The time for the flow to reach steady state was viscosity dependent with high viscosities (on which the porous media has more effect) being much faster (around 0.05 s) compared to 0.4 s for a viscosity of 0.01 Pa s. The cpu time required is 90 minutes per second of simulation time.

SLURRY FLOW IN THE MILL

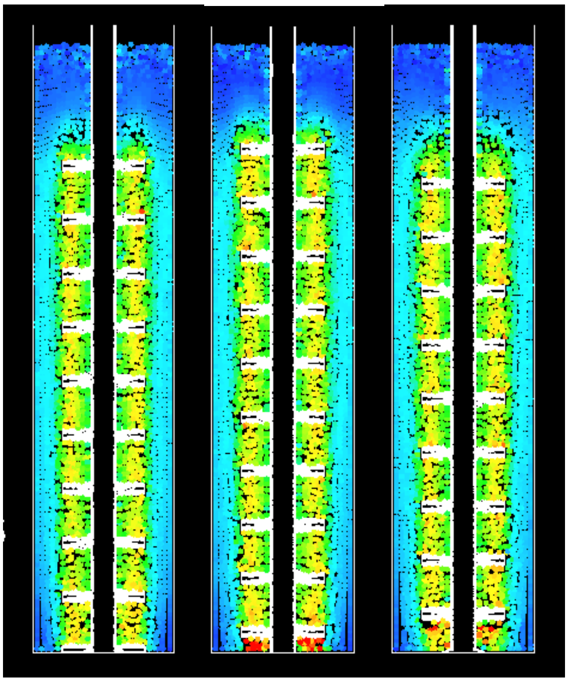

Figure 4: Slurry coloured by its speed with blue being close to stationary and red is 0.55 m/s in a cross-section through the center of the screw. The intersections of the screw can be seen rising over time with high speed fluid racing into the gap under the shoe of the screw.

Figure 4 shows the flow in a vertical cross-section through the center of the screw for a viscosity of 0.1 Pa s. Each intersection of the screw with the sectioning plane appears as a horizontal extension on either side of the central shaft. The fluid motion in the left frame is highest in an annular band just inside the outer tip of the screw. This fluid is swirling strongly and being lifted axially by the screw. The higher flow speeds within the screw result from the lower media solid fraction which creates a much higher permeability there and therefore enables the fluid to be much more mobile. At a large radius, the fluid speed is moderate. This corresponds to both a reasonable swirling component and a downward axial flow. At the bottom of the mill, the fluid in the lower corners is fairly quiescent as this represents a stagnation point. At the top of the charge, slurry within the media is little affected by the recirculating media and slurry motion below. The effect of the screw does not propagate much above where the screw blade ends and the rotating shaft above this has little effect on the charge motion. The three frames show the configuration at 0.1 s intervals. The intersections of the screw can be seen rising over time. High speed fluid races into the gap under the shoe of the screw (where media cannot easily reach).

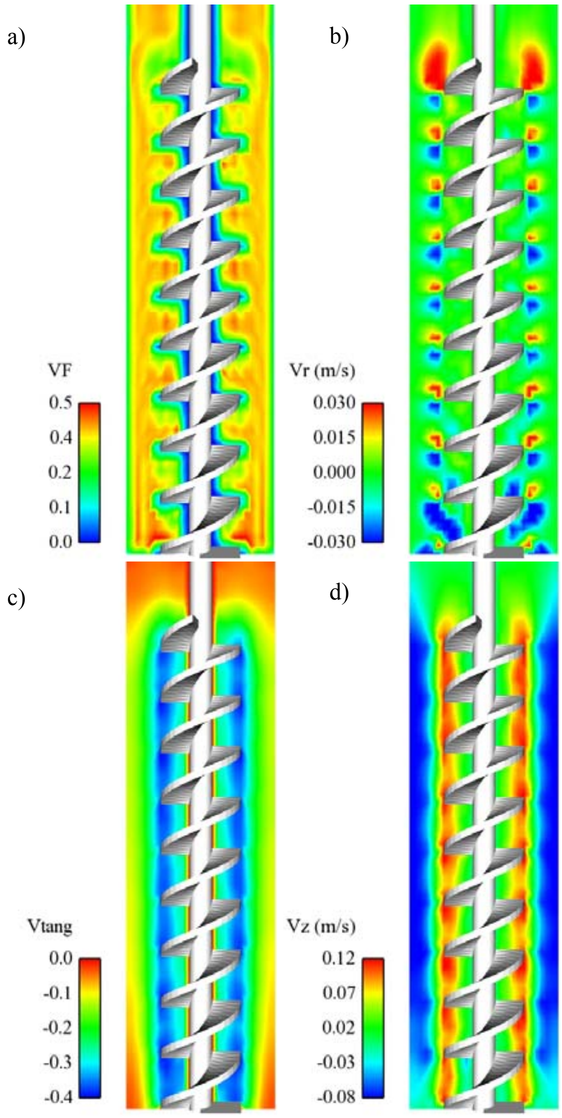

Figure 5: Steady-state distributions of: a) solids fraction; b) radial, c) tangential and d) axial velocities for the high viscosity ($\mu = 0.1$) SPH slurry in the tower mill

The flow is steady in a frame that co-rotates with the screw. In order to better visualise the flow structure we also average the SPH particle properties onto a rotating grid (as we did for the DEM particles). This allows us to identify more easily coherent steady flow structures.

Figure 5 shows the average slurry distribution and flow throughout the tower mill charge. Figure 5a shows the slurry coloured by fluid density in a vertical cross-section of the mill. The fluid fraction is fairly uniform throughout the mill at around 0.4, except in the region between the screw flights where it rises to around 0.5. We also observe a region of higher fluid concentration entering the screw (VF ~ 0.5) at the floor of the mill. The green band tight around the screw is an aliasing effect of the screw in the data averaging.

Figures 5b,c&d show the flow field for the slurry which unsurprisingly is generally very similar to that of the solid charge. The radial fluid velocities in Figure 5b demonstrate a vortex pattern at the blade edge (like that of the solid charge in Figure 3b), but the flow structures for the fluid vortices are fairly constant in strength along the full mill height, whereas for the media they increase in strength with height. The radial speeds in these structures are around three times higher than those in the solid phase. The distribution of fluid tangential speed (see Figure 5c) is almost identical to the flow of the grinding media. The radius at which the peak tangential speed occurs for the fluid is just inside the screw edge, whereas for the media it occurs just outside. Figure 5d shows vertical fluid velocities in the mill. The distribution patterns are very similar for the media and slurry, rising in a core region with the screw and falling in an outer annulus between the shell and the screw. However, the speeds in the up and down flows are stronger for the slurry which appears to be circulating faster than the media The high speed up flow is more narrowly concentrated in a band just inside the screw tip. The effects of the edge vortices are visible in the oscillating strength of the vertical speed.

EFFECT OF SLURRY VISCOSITY

We now consider the effect of different viscosities, μ, on slurry transport through the mill, comparing results of the high (0.1 Pa s) and low (0.01 Pa s) viscosities. Figure 6 summarises the differences between the two cases. The fluid pressure distribution differs significantly for the different viscosities as is shown in Figure 6a. Fluid pressure increases with depth in the mill for the low viscosity case, comparable to a simple hydrostatic loading in a fluid filled tank. This indicates that much of the weight of the slurry is transmitted through the fluid to the bottom of the mill rather than to the media. Higher pressures are experienced along the bottom third of the walls and into the corners, as well as inside the lower third of the screw. The pressure is greatest just underneath the screw blade. In contrast, for the higher viscosity the pressures are much lower and are almost uniform along the length of the mill. This reflects the much stronger influence of the media when the viscosity is high. The weight of the slurry is supported by being transferred to the media which in turn transmits it to the mills walls giving a non-hydrostatic distribution. A region of moderate pressure is observed at the top of the screw.

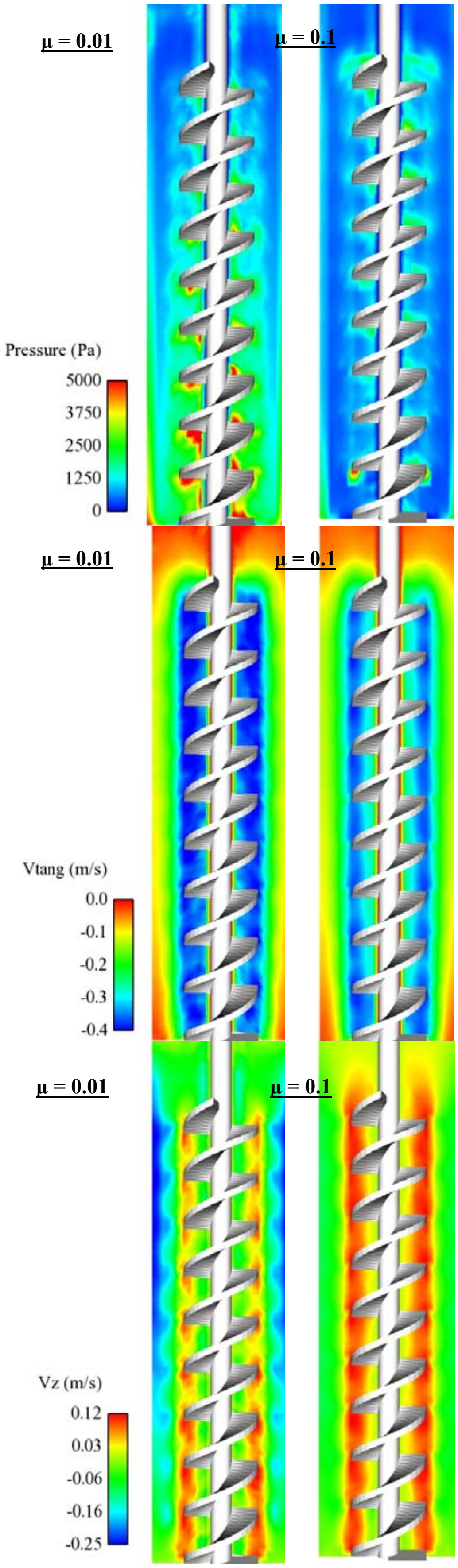

Figure 6: Steady-state distributions for the two different viscosity slurries: a) pressure; b) tangential and c) axial velocities.

The high pressures exerted on the low viscosity slurry force the fluid at the bottom of the mill into the screw at higher speed (as shown in Figure 6b). Once in motion, it is less impeded by drag from the media. So the fluid swirls around the mill with a tangential speed that is greater than for the media but which is still less than the tangential velocity of the screw surface. Drag forces on the high viscosity fluid are large enough to constrain the slurry to travel at speeds that are much closer to that of the media.

The vertical velocities are also very different for the two viscosity cases considered, as shown in Figure 6d. The high viscosity slurry is strongly transported upwards inside the screw at a similar rate to that of the media (see Figure 3d). Inside the screw there is a lower solid fraction for the media and a corresponding higher permeability. This permits greater mobility of the fluid within the screw. As such, the screw and rising media are less able to drag the fluid upwards. However, this is at least partially balanced by the vertical pressure gradient that is observed (Figure 6a). The net result is that the peak speeds are similar for the two viscosities, but the volume of high speed flow is smaller indicating that the volumetric recirculation rate is lower for the lower viscosity fluid. In the upper two-thirds of the mill, there is a very strong downwards flow (about three times faster than the media but concentrated in a narrow region close to the mill shell) for low viscosity slurry.

In actual operation, the slurry within the mill tends to settle to a limiting density with a viscosity corresponding to the nearly settled density. Hence, controlling the proportion of very fine particles by effective classification (outside of the mill) will help to keep the slurry viscosity in the range where it does not completely damp out a substantial proportion of the grinding action.

CONCLUSION

We have presented here an SPH computational fluid model for slurry transport inside a tower mill. It is based on DEM simulation of the solid charge of grinding media which is used to define a dynamic porous media. The porosities and velocities are then 1-way coupled to the SPH fluid. This is reasonable because of the limited capacity of the fluid to influence the media motion in this system.

For the slurry model, a number of flow characteristics in the mill were identified specific to the fluid transport:

- A reduced solid fraction inside the screw results in a higher permeability and allows greater mobility for the fluid phase.
- Vortex structures were observed around the edges of the screw blade. This consists of an outward radial flow from the top blade surface and return inward flow underneath the blade. The magnitude of these radial speeds for the fluid was shown to be higher than the media flow and was uniform with height.
- The peak tangential speed of the slurry flow was observed to occur at a different radial position to that of the solid charge, just inside the screw edge.
- Slurry pooled at the top of the charge, above the top of the screw was quiescent and largely unaffected by the rotation of the screw.

Slurry viscosity was found to strongly influence the flow and its transport rate. The pressure distribution and flow field were both shown to be sensitive to the viscosity. For lower viscosities (such as 0.01 Pa s), the pressure distribution is broadly hydrostatic, and the fluid phase is more mobile and able to move more independently of the solid charge. The fluid up flow is concentrated in a narrow band just inside the screw top and with high speed flow down near the mill shell. At higher viscosities, pressures are lower and more uniform. The drag from the media dominates resulting in the slurry being pulled around the mill by the solid charge. The up flow is of a similar speed to that of lower viscosities but the up flow region is much broader resulting in a larger volumetric recirculation rate. The down flow is much more uniform but is slower and occurs over a larger cross-sectional area of the mill.

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