DEVELOPMENT OF RHEOLOGY MODEL FOR COMPUTATIONAL FLUID DYNAMICS SIMULATION OF SAND DEPOSITION INTO SOFT TAILINGS

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ABSTRACT
In this paper a viscosity model for an oil sands fine tailing slurry is developed based on viscosity measurement data obtained using vane rheometer. The static yield stress of the slurry with varying solid contents is measured and numerically matched using a computational fluid dynamics (CFD) model to evaluate the static yield stress measurement. Comparison of the simulated torque with the measured torque is made in order to validate the CFD model. From the simulations, the flow field and yield surface are analyzed and further investigations into the flow pattern and yield surface for Herschel-Bulkley fluid and Casson fluid are carried out in order to evaluate the assumptions on which the yield stress measurement is based. The simulation results agree with the work done by Yan (1997) and others. The assumptions are validated using CFD models.

RESUMÉ
Un modèle de viscosité pour la boue fine mûre d'équeutage est obtenu a basé sur les données des mesures de viscosité. L'effort d'fléchissement statique de la boue est mesuré en utilisant un rhéomètre de palette. Le modèle de viscosité est entré dans un Computational Fluid Dynamics modèle (CFD) pour évaluer la mesure statique d'effort d'fléchissement. La comparaison du couple simulé avec la valeur mesurée est faite afin de valider le modèle de CFD. Puis le champ d'écoulement et la surface de rendement sont analysés ont basé sur le modèle de CFD. Les résultats de simulation sont conformes au travail effectué par d'autres. Les prétentions sont validées en utilisant des modèles de CFD.

1. INTRODUCTION

Suncor's and Syncrude's tailings ponds currently contain, or will contain, significant volumes of soft materials that must be remediated in some way to achieve their reclamation objectives. Although there is a large body of knowledge available surrounding the deposition of sand slurry into water, little is known about deposition of sand slurry into soft deposits, such as CT, MFT and thickened tailings. These deposits are additionally complicated with non-uniform properties in that they have a viscosity, yield strength and density which is a function of age, depth in the pond, the sand to fine mineral grain size ratio and insitu water chemistry. The major uncertainty is the degree of mixing of the sand slurry with the insitu soft deposit and the resulting engineering behavior of the mixture related to development of a stable reclaimable surface with tolerable long-term settlements. Failure to optimize these issues is likely to increase the difficulty, volume and cost of MFT transfer and/or to increase the cost of reprocessing of materials in order to achieve the reclamation objectives. These incremental costs could easily reach the 10's of millions of dollars range.

Understanding the rheological properties of MFT is crucial to optimise the handling with the soft tailings. MFT possesses complex rheological properties (FTFC, 1995) and it demonstrates a thixotropy, yield stress and shear thinning. In this paper, the static yield stress of MFT slurry with different solid contents is measured and curve-fitted using the equation proposed by Coussot 1997. The viscosity of MFT has been measured using a viscometer. A viscosity model suitable for application to computational fluid dynamics (CFD) method was obtained based on the measured data. Then, computational fluid dynamic (CFD) methods were applied to simulate the vane shear tests. Assumptions made in interpreting vane shear test data are discussed. The rheological property data from the literature will be also be used in CFD simulations in order to evaluate the flow pattern and yield surface of the fluid with different viscosity properties under vane shear tests.

2. EXPERIMENTS

2.1 Measuring Yield Stress via Vane Shear Tests

Avramidis et al. (1991) and Turian et al (1993) showed that the yield stress determined by the vane method is an intrinsic rheological property of a dense Non-Newtonian slurry. In order to measure the yield stress of the slurry composed of various solid contents, a Brookfield R/S Soft Solid Tester was used in this study to measure the yield stress of the slurry. The material used in the experiments was MFT slurry with various solid contents by weight. The fines content remained identical for all the yield stress measurements in an effort to exclude the influence of this variable on the measured yield stress. Slurry with different solid contents are produced by mixing MFT from Syncrude's tailing pond with different volumes of pond release water. Pond release water is used to ensure aqueous chemistry is unchanged in the specimens. The particle size distribution of MFT is shown in Figure 1. The samples of MFT contained 39.0% solid content and 92.5% fine content. For a slurry with a solid content greater than

39%, centrifuged MFT with a solid content of 60.1% and fines content of 92.5% was diluted to the desired solid content by mixing it with release water. The prepared MFT slurry was mixed for 3 minutes prior to the viscometer measurement in order to obtain a homogeneous clay-water matrix. The slurry was allowed to "rest" for 2 minutes in order to preclude the effects of fluid movement on the measured yield stress. Effects of segregation of the slurry on the yield stress value are neglected due to its high fine content. Table 1 and Figure 2 show the static yield stress measured using the vane shear method. It can be seen that the yield stress increases as solid content increases and an asymptote for yield stress curve exists when the solid content is close to 61%. The yield stress data can be regressed using the following equation (Coussot 1997):

$$\tau_c = ce^{(s\phi)} \quad [1]$$

where τ_c and φ are static yield stress and solid volume fraction respectively, c and s are fitting parameters, which are 1.532 and 13.713 respectively for the data presented in Table 1.

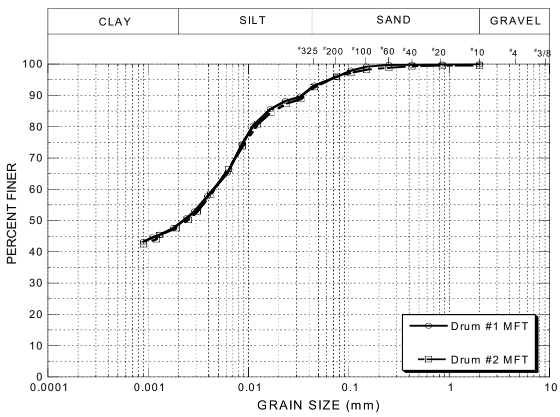

Figure 1 Particle size distribution of MFT

Table 1 Static Yield Stress for Slurry with Different Solid Contents

Solid Content (%)	Solid Volume Fraction	Static Yield Stress (Pa)
27.41	0.127	9.29
40.91	0.210	26.07
49.30	0.272	58.98
60.05	0.366	246.97

2.2 Measuring Viscosity via Viscometer

The slurry viscosity was measured using a Brookfield DV-II+ Programmable Viscometer. Cylindrical spindles were used for these tests. The measured results are shown in Figures 3 and 4. Attempts were made to fit the relationship between shear stress and shear strain rate using a Power Law Model, Bingham Plastic Model, Casson Model, Herschel-Buckley Model and Sisko Model. From Figure 4, it can be seen that a linear curve can be obtained in log-log plot. Consequently, a logarithmic model in the form of:

$$\mu = 10^{(a+b*\log(\dot{\gamma}))} \quad [2]$$

was adopted to regress the relationship between viscosity and shear stress. The parameters are shown in Table 2. The parameters can be related to solids content by regression. Figure 5 shows the variation of regression parameter a and b with solids content of the slurry. From this data, curve fitting can be applied to obtain the relationship between regression parameters and solids content:

$$a = -2.3885 + 0.12102s - 0.0008079s^2 \quad [3]$$

$$b = -0.7666 - 0.002714s \quad [4]$$

where s = solid content of the slurry (%).

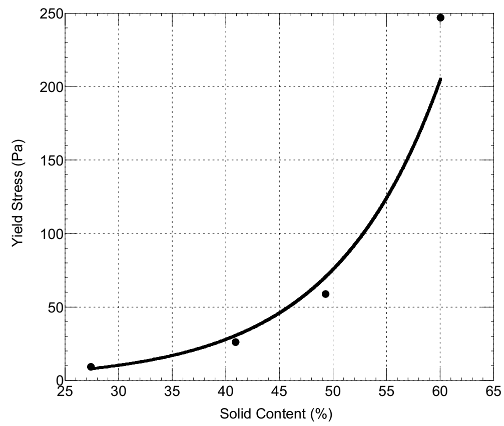

Figure 2 Static yield stress versus solid content (measured from vane shear tests)

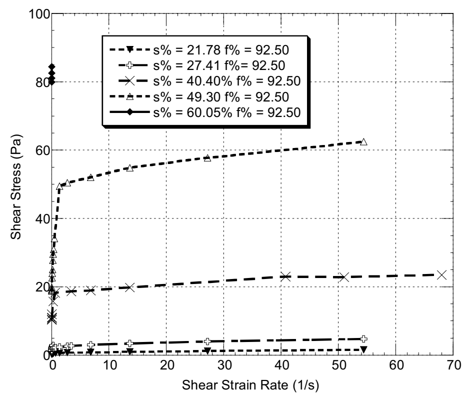

Figure 3 Shear stress versus shear strain rate for slurry with different solid contents

From Figure 4 it also can be seen that the viscosity of the slurry decreases as shear strain rate increases and the slurry viscosity at higher solids content is greater than for lower solid contents.

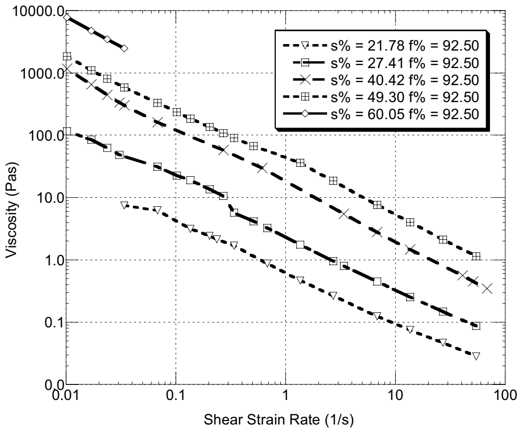

Figure 4 Apparent viscosity versus shear strain rate for slurry with different solid content

Table 2 Parameters for Viscosity Regression Equations

Parameter a	Parameter b	Solid Content (%)
-0.1971	-0.798	21.78
0.4137	-0.8774	27.41
1.2039	-0.9035	40.91
1.5657	-0.8383	49.30
1.9908	-0.9549	60.05

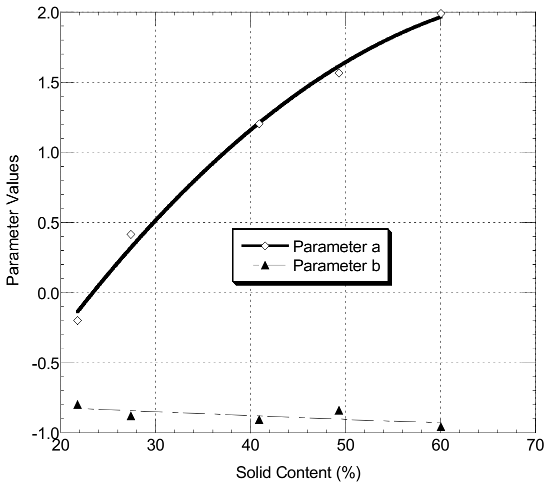

Figure 5 Parameter a and b in viscosity regression equations versus solid content of MFT slurry

3. COMPUTATIONAL FLUID DYNAMICS SIMULATION

Barnes (1999) questioned the existence of yield stress. He concluded that soft solids will demonstrate a creep behavior when the stress is below the apparent yield stress and a Newtonian-plateau viscosity can be used to describe the creep behavior. The yield stress is more or less related to our capability of measuring the shear stress at very tiny shear strain rate. Increasingly, the utility of the vane shear test to measure yield stress of a Non-Newtonian fluid and soft solids slurries is being recognized. Several authors (Avramidis et al. 1991; Turian et al. 1993) have shown that the yield stress determined by the vane method is an intrinsic, instrument-geometry indifferent rheological property of the concentrated Non-Newtonian slurry. From the world of geotechnical engineering and the use of vane shear tests to determine undrained shear strength, it is understood that several assumptions are involved in calculating the yield stress parameters using the vane method. It is almost always assumed that an imaginary cylinder with the same dimensions as those of vane blades is formed when the slurry yields under shearing by the vane. A yield surface coinciding with the imaginary cylinder surface is assumed in the interpretation of the test results. It is also assumed that the fluid between two adjacent vane blades is stationary in relation to the movement of blades - that is no secondary flow occurs when shearing the slurry in vane tests. The most important assumption is that the distribution of the shear stress on the yield surface is uniform and the magnitude of the shear stress is equal to the yield stress of the Non-Newtonian slurry (Nguyen et al. 1983; Keentok et al. 1985).

Several authors have verified these assumptions. Barnes et al. (1990) confirmed the existence of the fluid cylinder within the periphery of vane blades. Keentok (1985) demonstrated that the stress concentration at the tips of the blades, and the diameter of the fluid cylinder is larger than the vane diameter. Yan et al. (1997) evaluated the existence of the yield surface for viscoelastic and plastic fluids in a vane viscometer using finite element method. They also validated the assumption of uniform shear on a rotating cylinder of material included in the blades of a vane. They further concluded that for Herschel-Buckley and Casson fluid, a rotating rigid cylinder of fluid is attached at the vane blades and the shear stress on the surface of the fluid cylinder is uniformly distributed.

Within the world of soil mechanics and the measurement of undrained shear strength on soft deposits, De Alencar (1988) challenged the assumption of uniform distribution of the shear stress over the cylinder surface for the progressive failure in the vane test. They used a strain softening finite element model to evaluate the shear stress distribution around the perimeter of the vane and concluded that the stress distribution is not known and the assumption of uniform mobilization of shear strength will lead to an incorrect evaluation of the peak strength of the material.

In this paper, computational fluid dynamic (CFD) using finite element based finite volume method will be used to evaluate the assumptions in interpreting the vane shear tests results and explore the shear conditions within the test. The yield surface of MFT, Herschel-Bulkley fluid and Casson fluid will be evaluated in three dimensions. A commercial CFD package – CFX 5.7 was used to simulate the flowing of fluids in the vane rheometer.

Steady state, quasi transient and transient calculations are three methods that have been applied for simulating the interactions between the rotor and stator (Belardini 2003). The rotor refers to the vane and the stator is the mixing vessel. Although transient rotor-stator methods using a sliding mesh provides a more accurate time solution, excessive computing resources required for this method limits its practical applications. Given that the mixing vessel contains no baffles to cylindrical flow, the frozen rotor interface method was applied for the simulations presented in this paper.

The geometry of the vane is shown in Figure 6. The diameter of the vane blades is 20 mm and the height is 40 mm. The vane is immersed into a beaker with an internal diameter of 80.13 mm and a height of 90 mm. The computing domain is subdivided into rotationary and stationary parts, with the rotationary domain rotating with vane blades. The mesh is also shown in Figure 6.

In total, 310,505 tetrahedron elements were used in the simulations. As homogeneity of the measured slurry was assumed, a single phase model was applied in the simulations. In the experiments, turbulent flow was avoided in order to obtain an accurate yield stress measurement. Consequently, laminar flow was assumed for the CFD simulations. In the following sections, MFT with solids content of 40.4% is simulated. Following that, Herschel-Buckley and Casson fluids will be evaluated and the results compared to similar simulations reported in the literature.

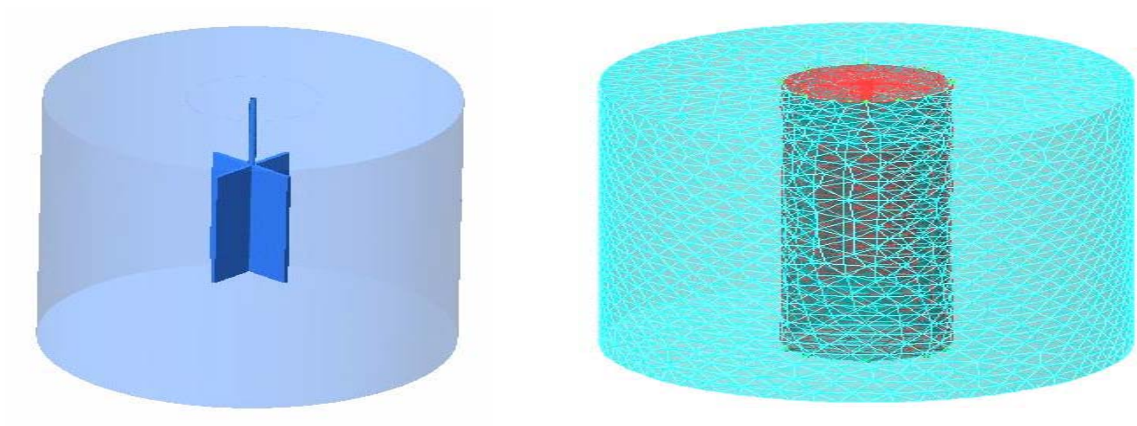

Figure 6 Geometry and mesh of vane rheometer

3.1 CFD Simulation of Yield Stress Measurement for MFT Slurry

The viscosity model for MFT based on the regression of the measured viscosity data was applied in the CFD model (Figure 4). The viscosity equation for MFT was as follows:

$$\mu = 10^{\,1.2039-0.9035\log(\dot{\gamma})} \qquad [5]$$

A non-slip wall boundary condition was set for the vane blades and the shaft of the vane. The domain containing the vane was assumed to rotate at an angular velocity of 0.05 radian/s.

Figure 7 shows the variation of measured and simulated torque with time. Although a slight discrepancy between measure and simulated torque can be seen, the trends of the simulated torque variation with time agree reasonably well with that of measured torque. The peak torque magnitude, which occurs during the experimental yield stress measurement, was captured by the CFD model.

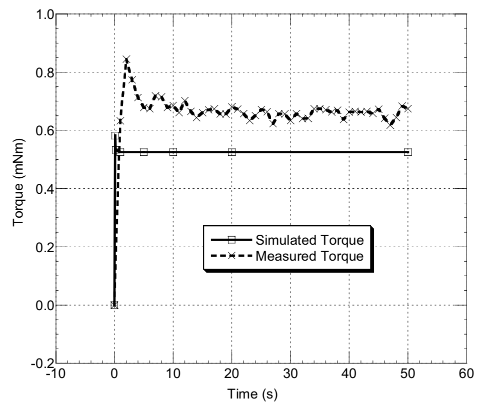

Figure 7 Comparison of measure and simulated torque for measuring the yield stress of pure MFT

The contours of shear strain rate on the plane passing through the middle of the vane blades are shown in Figure 8. It shows that the shear strain rate is almost uniform in the circumferential direction except for the higher shear strain rate in the proximity of the tip of the blades. In order to evaluate the shear strain rate over the virtual fluid cylinder surface in detail, the shear strain rate over a quarter of the circumference (at a radius equal to the tip of the vanes) was computed and is shown in Figure 9. Noting that the blades are located at $\theta = 0°$ and $\theta = 90°$, it is reasonably clear that the mobilized shear strain rate is not uniform. In addition, the maximum shear strain rate occurs around the vane blade tip. As expected, the minimum shear strain rate appears between two blades, which is consistent with experimental observations and experience with vane shear testing in geotechnical engineering.

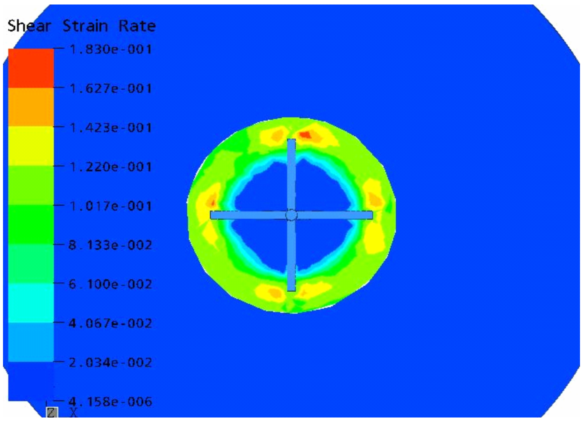

Figure 8 Shear strain rate for MFT yield stress measuring

Shear stress along the same circumferential curve discussed above is shown in Figure 10. Since the viscosity is dependent on the shear strain rate, the shear stress curve in Figure 10 does not illustrate the same trends as that of shear strain rate shown Figure 9.

However, two peak values of shear stress are shown in Figure 10 and they correspond to the shear stress for the fluid particles around the blades tip. Although the distribution of shear stress is not completely uniform, the range of the variation is small. The shear stress distribution on the cylindrical surface with radius of 0.010 m is presented in Figure 11. It can be seen that except for the concentration of shear stress close to the edge of the blades, the shear stress distribution is almost uniform.

The shear stress distribution along a line in the radial direction, which is a bisector of the vane blade on the horizontal section of the vane, is shown in Figure 12. It can be seen that the peak value occurs inside the imaginary cylinder surface with radius of 0.010 m.

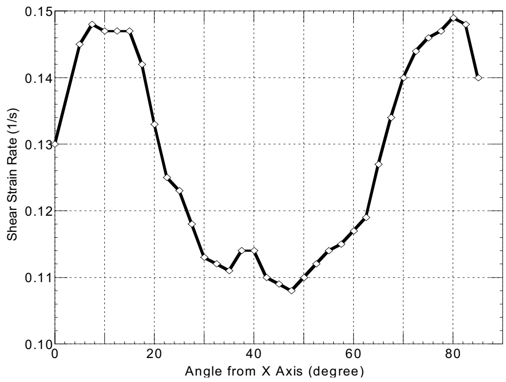

Figure 9 Shear strain rate for MFT along a curve with radius of 0.010 m on the horizontal mid-plane passing through the blades

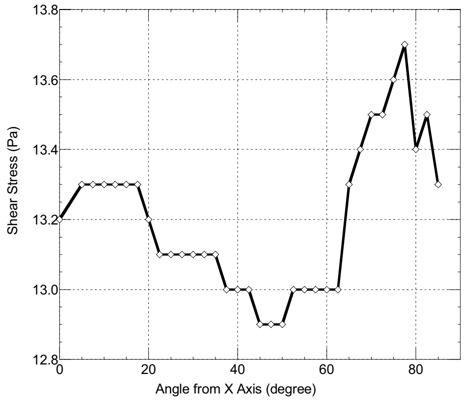

Figure 10 Shear stress for MFT along a curve with radius of 0.010 m on the horizontal mid-plane passing through the blades

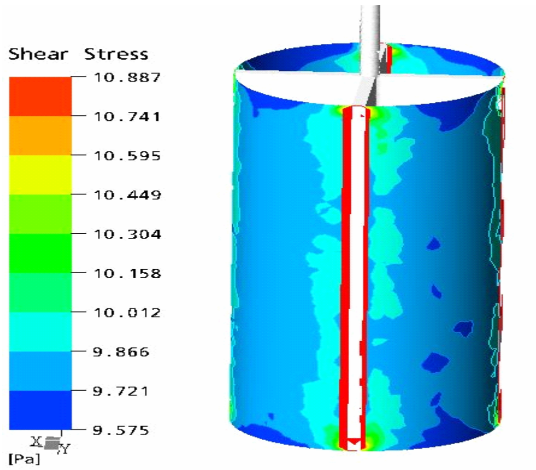

Figure 11 Distribution of shear stress over the imaginary cylindrical surface with radius of 0.010 m

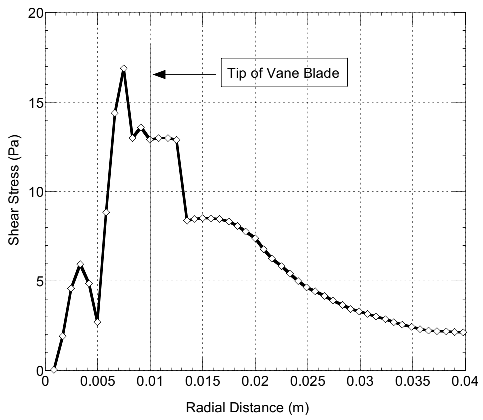

Figure 12 Shear stress on the curve with equal distance to two adjacent blades (in radial direction)

The shear strain rate on a plane passing through the vane blades is shown in Figure 13. If the yield surface is the surface where the shear strain rate is greatest, the shape of the intersection of the yield surface with the horizontal plane can be approximated as a circle. The peak of the shear strain rate is almost the same, indicating further that the assumption of cylindrical yield surface is valid for MFT. The shear strain rate inside the circle with radius equal to that of vane blades is close to zero, which supports the assumption that the fluid entrapped in the imaginary cylinder is acting in a rigid manner and there is no secondary flow between the adjacent blades.

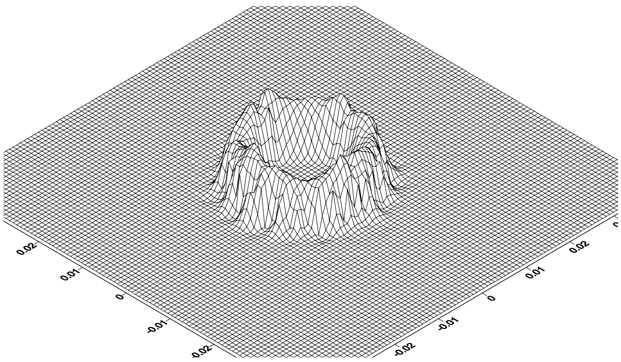

Figure 13 Shear strain rate surface plot for MFT slurry over the plane passing through the middle of the vane

The velocity vectors on the plane passing through the middle of this plane is shown in Figure 14. Approximately uniform velocity in the tangential direction can be observed. It also can be seen that the velocity of the fluid outside the imaginary fluid cylinder is very small and the fluid between the vane blades rotate at the same angular velocity as that of vane blades.

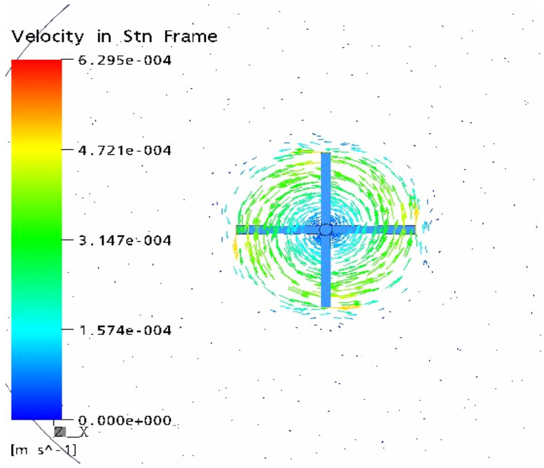

Figure 14 Vector of velocity on the plane passing through the middle of the vane blades for MFT

4. EVALUATION OF THE YIELD SURFACE FOR HERSCHEL-BUCKLEY AND CASSON FLUIDS

The viscosity model chosen for CFD simulations will exert a large influence on the simulated response of the vane shear tests. To explore this sensitivity, the viscosity model reported by Yan (1997) will be used. The goal of these simulations was to validate the model used in the above simulation and to further evaluate the assumptions in interpreting vane shear tests for these high solids (mostly fines) slurries. Firstly, a Herschel-Buckley plastic fluid is evaluated followed by Casson fluid model. The distribution of velocity, shear strain rate and shear stress will be compared with those reported in the paper by Yan (1997).

4.1 CFD Simulation of Herschel-Buckley Fluid

The Herschel-Buckley viscosity model used here is the same as that in the paper by Yan (1997). The viscosity model takes the following form in CFD model:

$$\mu = \begin{cases} \dfrac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1} & if \quad \dot{\gamma} > \dot{\gamma}_c \\ \dfrac{\tau_y}{\dot{\gamma}_c} + K\dot{\gamma}_c^{n-1} & if \quad \dot{\gamma} \le \dot{\gamma}_c \end{cases} \qquad [6]$$

where $\dot{\gamma}$ and $\dot{\gamma}_c$ are shear strain rate and critical shear strain rate respectively, τ_y is yield stress, and K and n are a constant proportionality and a power index respectively. Two simulations were carried out for the Herschel-Buckley fluid. The values of K, n and τ_y are 1.0 Pa·s, 0.5, 100 Pa for both of the simulations respectively. The critical shear stain rates are 0.001 and 0.025 radian/s, respectively.

4.2 CFD Simulation of Casson Fluid

As well, simulations were conducted using a Casson viscosity model. The parameters used in Casson fluid simulation were adopted in Yan's paper (1997). The viscosity model was modified in order to avoid machine overflow errors when the strain rate was close to zero and it is shown in Equation. (7):

$$\mu = \begin{cases} \left(\left(\dfrac{\tau_y}{\dot{\gamma}} \right)^{1/2} + \mu_p^{1/2} \right)^2 & if \quad \dot{\gamma} > \dot{\gamma}_c \\ \left(\left(\dfrac{\tau_y}{\dot{\gamma}_c} \right)^{1/2} + \mu_p^{1/2} \right)^2 & if \quad \dot{\gamma} \le \dot{\gamma}_c \end{cases} \qquad [7]$$

where μ_p is plastic viscosity. The yield stress and plastic viscosity used in the simulation were 1.0 Pa.s and 100 Pa, respectively. The angular velocity of the vane is 0.01 radian per second.

4.3 Comparison of the simulation results

Since the Herschel-Bulkley fluid and Casson fluid models used in the simulation had the same yield stress and the rotation speed of the vane blades were the same, comparison of the shear stress distribution on the imaginary cylinder surface can be made. This comparison is illustrated in Figure 15. While similar variations (trends) in shear stress were predicted for each fluid model, the mobilized shear stress on the shear surface were different.

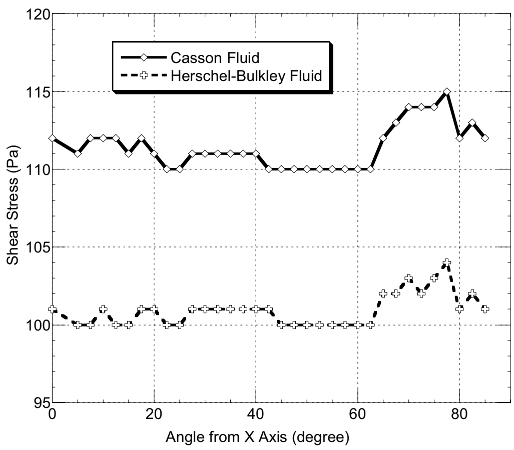

Figure 15 Comparison of shear stress distribution on the imaginary cylinder surface

In the Herschel-Buckley and Casson viscosity model applied in the CFD simulations, the critical shear strain rate appears in the viscosity equations. The critical shear strain rate is a shear strain rate value which determines the actual viscosity used in the calculations. Below this value, the plateau viscosity is used and above this value the corresponding viscosity model is used. Applying a critical shear strain rate in the numerical simulation was a simplification of the actual viscosity model. The effects of the critical shear strain rate on the shear stress distribution are shown in Figure 16.

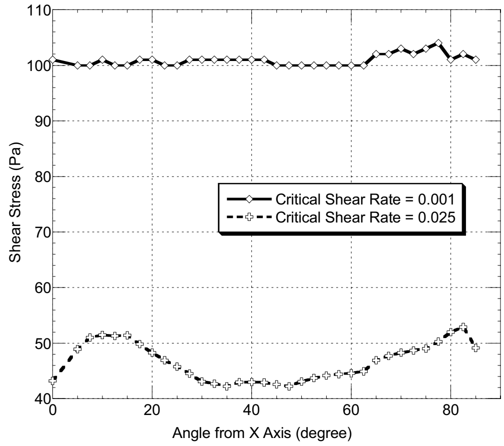

Figure 16 Comparison of shear stress distribution for Herschel-Buckley fluid using different critical shear rate

Considering the fact that all simulation parameters were kept the same except for the critical shear strain rate, one can conclude that this value has a great influence not only on the magnitude but also the distribution of the shear stress on the imaginary shear surface. It can be seen that the distribution of shear stress for the simulation with critical shear strain rate of 0.001 radian per second is more uniform than that with the critical shear strain rate of 0.025. Figures 17 and 18 also show that the shear stress distribution on the imaginary cylindrical shear surface for the critical shear strain rate of 0.001 and 0.025 radian per second, respectively.

5. CONCLUSIONS

The viscosity model obtained from regression of the viscosity measurement data for MFT was used successfully in CFD simulations. Although no yield stress was explicitly specified in Equation (5), the simulations captured the properties of other viscosity models for a Non-Newtonian fluid. When the shear strain rate was very small, the viscosity was very high. The viscosity model can be used to simulate the yield stress measurement for MFT.

Yield stress obtained from experimental measurements using a vane rheometer was thought to be a more reliable method than curve-fitting or extrapolation methods. However, the vane shear method is based on several assumptions which required careful evaluation. CFD simulations of the experimental measurement process demonstrated that the shear strain rate, velocity of the fluid and shear stress on the imaginary cylinder surface are not completely uniform. The degree of uniform distribution of the shear stress on the imaginary cylinder surface depends on the viscosity of the fluid and critical shear strain rate used in the CFD model.

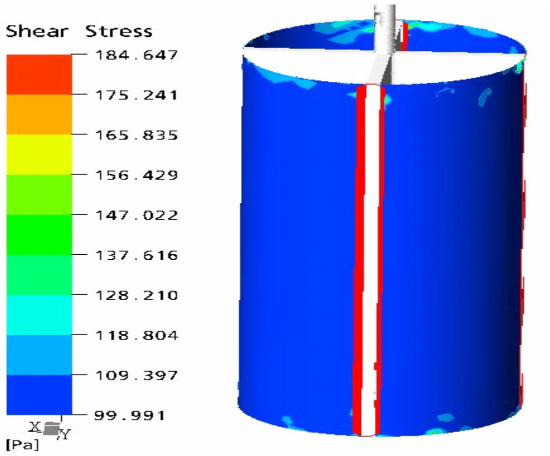

Figure 17 Shear stress distribution on the imaginary cylinder surface for Herschel-Buckley fluid using critical shear strain rate of 0.001 radian/second

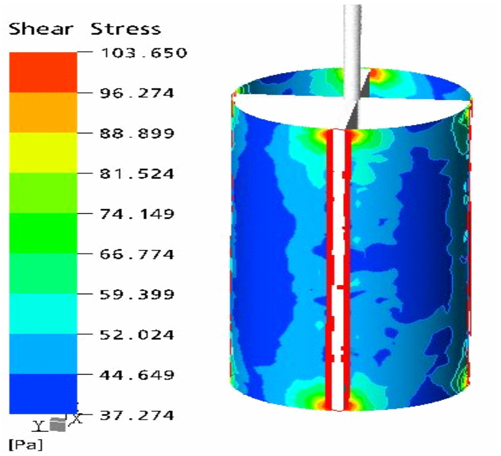

Figure 18 Shear stress distribution on the imaginary cylinder surface for Herschel-Buckley fluid using critical shear strain rate of 0.025 radian/second

For a fluid with high viscosity, the assumption of uniform distribution of the shear stress is valid, which can be seen from Figure 16, 17 and 18, as the only difference in the two simulations is the actual fluid viscosity. The assumption that a rigid zone forms in two adjacent blades appears to be valid for fluid with high viscosity.

6. ACKNOWLEDGEMENTS

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