Plant design for slurry handling

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Introduction
The minerals processing industry is under continuous pressure from environmental, legal and financial quarters to use less water and operate at higher concentrations directly affects slurry flow behaviour. Using the Bingham plastic rheological model, the impact that slurry rheology has on transitional pipe flow, particle settling in laminar shear flow, losses in valves and fittings, centrifugal pump derating and launder flow are presented.

Rheological characterization
Slurry rheology (viscous character) is a dynamic property of microstructure. When the slurry is stationary, the attractive forces between particles or agglomerates form a three-dimensional structure, which extends to the walls of the container. The shear stress required to rupture this structure and initiate flow, is called the yield stress. Below this stress, the material behaves like an elastic solid. As shear stresses and shear rates increase, the agglomerates gradually reorientate and disintegrate, resulting in a decrease in the viscosity of the material. This process is known as shear thinning. At very high shear stresses and shear rates, the reorientation and disintegration process reaches equilibrium, and the viscosity becomes constant.

Although this portrayal of the relationship between viscosity and microstructure is idealized, it is useful for engineering purposes. The simplest steady state, time independent rheological model, which can accommodate the behaviour described, above is the Bingham plastic model. This model can be formulated in terms of shear stress $\tau$; $\tau = \tau_y + K \gamma$; or viscosity $\eta$; $\eta = \tau / \gamma = \tau_y / \gamma + K$. where $\tau_y$ is the yield stress, $K$ is the plastic viscosity and $\gamma$ is the shear rate or velocity gradient. The two terms on the right-hand side of Equation 2 will be equal when

$\gamma_y = \frac{\tau_y}{K}$. [3]

Synopsis
The key issue when designing plants for slurry handling, is understanding the slurry environment. Pressure to use less water and operate at higher concentrations directly affects slurry flow behaviour. Using the Bingham plastic rheological model, the impact that slurry rheology has on transitional pipe flow, particle settling in laminar shear flow, losses in valves and fittings, centrifugal pump derating and launder flow are presented.

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© The Southern African Institute of Mining and Metallurgy, 2006. SA ISSN 0038–223X/3.00 + 0.00. This paper was first published at the Western Cape Branch Workshop, Plant Design for Optimum Performance, 3 August 2005.
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The importance of the boundary shear rate \( \dot{\gamma}_b \) is that it marks the boundary between yield stress and plastic viscosity domination of viscosity. This is shown graphically in Figure 1.

The two terms on the right-hand side of Equation 2 each represent the asymptotes shown in Figure 1. It is significant to note from Figure 1 that the ordinate intercept (at a shear rate of unity) of the oblique asymptote is in fact the yield stress value \( \tau_y \). This illustrates the fact that—for practical purposes—the viscosity values for shear rates less than the boundary shear rate \( \dot{\gamma}_b \) are directly proportional to the yield stress. This serves to emphasize the importance of the yield stress value when operating in the region to the left of the boundary shear rate. The yield stress \( \tau_y \) is a strong function of particle properties, concentration and solution chemistry, with the plastic viscosity \( K \) usually being a weaker function of these.

Clearly, knowledge of the slurry rheology is of prime importance to understanding the slurry environment, and its determination would be one of the first steps in the design process.

Transitional pipe flow

The laminar/turbulent transition is of extreme importance for plant design, because at this point the behaviour of the fluid changes fundamentally. The manner in which slurry rheology affects transitional flow behaviour is critically important to understanding the slurry environment. For Newtonian fluids, such as water and oil, the location of the transition is well established and the calculation is simple. For systems conveying non-Newtonian slurries, however, this is not the case. Although an accurate method is available, it is computationally somewhat cumbersome.

However, for large, industrial sized pipes, the estimation of the laminar/turbulent transition velocity, \( V_c \), using this approach, resolves to a surprisingly simple relationship dominated by the yield stress, and which excludes pipe diameter and plastic viscosity:

\[
V_c = \frac{26 \sqrt{\frac{\tau_y}{\rho}}}{\dot{\gamma}_b}, \quad [4]
\]

where \( \rho \) is slurry density.

Yield stress domination of the transition behaviour is in fact to be expected, since it has been shown that for large pipes, the transition point always occurs to the left of the boundary shear rate \( \dot{\gamma}_b \) shown in Figure 1, in the yield stress dominated region.

Settling in laminar shear flow

Pipelines conveying non-Newtonian slurries in laminar flow will undergo laminar shear flow settling of the coarser particles. In the absence of any effective re-suspending mechanism, a bed will form, which could eventually block the pipe. The AMIRA P599/A project ‘High Concentration Suspension Pumping’ was initiated precisely to address this problem. These flows can be modelled using a generic two-layer model, which is usually applied to heterogeneous, settling slurries, as shown in Figure 2.

Figure 2, a plot of wall shear stress vs bulk shear rate \( (8V/D) \), illustrates the obscure nature of these flows. Although strongly heterogeneous, settled bed flow was observed for all four pipe sizes, but only the largest pipe shows evidence of the settled bed behaviour in Figure 2. In fact, in the two smaller diameter pipes, the experimental data show convincing evidence of only homogeneous behaviour.

If pressure gradient prediction were to be done for the larger pipe on this basis, Figure 2 clearly shows that under-prediction errors of 100 per cent or more will result. It is important to note that this behaviour is true even for slurries with a yield stress that is high enough to support the largest settleable solid particles.

Losses in valves and fittings

Losses in valves and fittings can form a significant portion of the total energy losses in the relatively short pipe run lengths typically found in minerals processing plants. This point is well illustrated by recent texts on the subject.

An exacerbating factor is that these losses become much more significant in laminar flow. Very little design information is available on loss coefficients in laminar flow, and is urgently needed. The FPRC has already begun producing such data for practical design purposes.
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The loss coefficient $k_v$ of a valve (or fitting) defines the head loss across the valve $H_{Lv}$ as a portion of the velocity energy head of the slurry:

$$H_{Lv} = k_v \frac{V^2}{2g}. \quad [5]$$

Figure 3 shows that the work at the FPRC provided experimental data over eight orders of magnitude of Reynolds numbers for the loss coefficient for three differently sized (12.5 mm, 25 mm and 40 mm) geometrically similar globe valves. This work was carried out using nine different Newtonian and non-Newtonian fluids on two different test rigs, demonstrating that dynamic similarity—in the broadest possible sense—can be achieved for valves and fittings. This data can therefore be used with confidence for accurate and efficient design purposes.

**Centrifugal pump derating**

Pumping head characteristics must be based on the pump performance for the fluid that must be pumped. Conventionally, manufacturer’s pump catalogue curves are presented for clear water performance only. When designing for slurry handling, these curves must be derated, and the usual approach is to determine the head and efficiency ratios (as slurry:water performance), referred to as HR and ER respectively.

For settling slurries, standard methods are available, which can usually be used successfully. For non-Newtonian slurries, there is less certainty, and methods based on the slurry rheology are presently under investigation.

The Walker and Goulas pump Reynolds number is an effective method to predict pump performance for non-Newtonian slurries. However, it is based either on the plastic viscosity only, or on an apparent viscosity, both of which present fundamental rheological problems. These problems arise immediately from examination of Figure 1—unless an accurate estimate of the shear rate within the pump can be defined, these values are meaningless. Sery and Slatter present a new analysis, $N_{Rep2}$ based on the pump geometry and the more comprehensive Herschel-Bulkley rheological model. Experimental data from centrifugal pump tests performed at the FPRC have been used to compare these two approaches, as shown in Figure 4.

It is of particular importance to be able to predict the performance of centrifugal pumps, since at high concentration, total cost comparison with PD pump systems need to be made over the life of the plant. Since the main issue in
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these comparisons is the capital cost of the PD pump system versus the running cost of the centrifugal pump, accurate derating of both head and efficiency is of prime importance. Figure 4 shows that both approaches appear to have similar merit, and work in this area is ongoing. However, what is clear from Figure 4 is that pump performance decreases significantly as the Reynolds number decreases below $1 \times 10^6$.

**Launder flow**

Launder are used extensively in the minerals processing industry. However, very little is known of the way in which the rheology of the slurry affects the behaviour of these flows, especially as the slurry becomes more viscous, and laminar flows predominate. Clearly, knowledge of this interaction is vitally important to the understanding of the slurry environment for plant design.

Our approach at the FPRC is to adopt the time-honoured approaches of engineering hydrodynamics, and develop a Reynolds number, which we could use to establish dynamic similarity.

For launder flow, the Fanning friction factor $f$ is given by

$$f = 0.079 \frac{Re^{0.25}}{\log (W&G Trend)}.$$

Using data from the experimental programme at the FPRC, this approach can be evaluated as presented in Figure 5.

Figure 5 shows that this approach has merit, and adequately models the interaction between slurry rheology and laminar launder flow behaviour. Figure 5 also shows that the transitional behaviour can be expected to be more complex than for pipe flow—and research continues in this direction.

**Discussion**

One of the hallmarks of research is that it asks more questions than it answers, and this discipline is no exception. This paper started by making definitive statements describing slurry rheology. While these statements are often adequate for engineering purposes, the truth is that slurry rheology depends on physical and chemical state, as well as the flow conditions themselves. There is much research still to be done. However, for those who need to make effective designs that work in the present, it is believed that the issues raised here will provide a basis for understanding the slurry environment—a vital precursor for sound design.

**Conclusions**

Our point of departure for this paper has been that sound design for slurry handling rests squarely on an understanding of the slurry environment. The manner in which slurry rheology affects flow behaviour in a number of typical plant design hydrodynamic contexts has been presented. Slurry rheology itself is, however, a complex topic, and research in this area is ongoing.
Acknowledgement

The author wishes to acknowledge the contributions of the staff and students of the FPRC.

References


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Figure 5—A 6% bentonite slurry flowing in a 300 mm rectangular flume

[Diagram showing Fanning friction factor vs. Re (Reynolds number), with data points and fitted curves.]