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THE DESIGN OF HYDRO-TRANSPORT SYSTEMS TO FACILITATE SUSTAINABLE INDUSTRIAL PRACTICE

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The industrial processing industry is under continuous pressure from environmental, legal and financial quarters to use less water, and designers and operators are obliged to consider the option of operating at higher concentration. As the concentration of fine particle industrial processing suspensions increases, viscous stresses also increase, and inevitably become non-Newtonian in nature. For some years, our research group has been researching the behaviour of high concentration non-Newtonian suspensions in pipes, valves and fittings, pumps and launders, and these will form the focus of the paper. The aim of this paper is to highlight the important practical aspects of these fundamental issues, and their implications for sustainable design for suspensions handling. In particular, the objective is to present the principal conceptual issues that underpin sound sustainable design. The full detail of the design process for handling suspensions is an extensive topic, beyond the scope of this paper, and the reader is referred to sources dealing directly with these for more detail (Paterson and Cooke). The important point to make at the outset is that the foundation of sound sustainable design for industrial suspensions handling does not revolve around the task of choosing or producing special materials and plant—although these are often required. The foundation lies rather in having a good understanding of the industrial suspensions' fundamental viscous properties (Paterson and Cook, Wasp et al 1977), which is the basis of this paper and our work at the industrial flow process research group.

KEY WORDS: non-Newtonian, design, pipes, fittings, pumps, launders.

NOTATION

f	Fanning friction factor (-)
g	Gravitational acceleration (m s^{-2})
H_{Lv}	Headloss in a valve (m)
K	Plastic viscosity (Pa.s)
K_v	Valve loss coefficient (-)
Re	Reynolds number (-)
R_h	Hydraulic radius (m)
V	Velocity (m s^{-1})
V_c	Critical velocity (m s^{-1})
γ	Shear rate (s^{-1})
γ_b	Boundary shear rate (s^{-1})
θ	Slope (-)
ρ	Density (kg m^{-3})

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τ	Shear stress (Pa)
τ_w	Wall shear stress (Pa)
τ_y	Yield stress (Pa)

1. INTRODUCTION

The key issue for sustainable plant design for fine particle industrial suspension handling, is understanding the process suspension environment. Conservational stress to use less water and operate at higher concentrations directly affects the suspension's flow behaviour. Using the Bingham plastic rheological model, the impact that process suspension rheology has on transitional pipe flow, particle settling in laminar shear flow, losses in valves and fittings, centrifugal pump de-rating and launder flow are presented.

2. RHEOLOGICAL CHARACTERIZATION

An industrial suspension's rheology (viscous character) is a dynamic property of microstructure (Slatter 2005). When the industrial suspension is stationary, the attractive forces between particles 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 industrial flow process design and operational 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 τ;

$$\tau = \tau_y + K\dot{\gamma} \quad (1)$$

or viscosity η;

$$\eta = \frac{\tau}{\dot{\gamma}} = \frac{\tau_y}{\dot{\gamma}} + K \quad (2)$$

where τ_y is the yield stress, K is the plastic viscosity and $\dot{\gamma}$ is the shear rate or velocity gradient. The two terms on the right-hand side of Equation 2 will be equal when (Slatter 2005)

$$\dot{\gamma_b} = \frac{\tau_y}{K} \quad (3)$$

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 that the ordinate intercept (at a shear rate of unity) is in fact the yield stress value τ_y. This illustrates the fact that 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 τ_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 industrial suspension's rheology is of prime importance to understanding the industrial suspension's environment, and its determination would be one of the first steps in the sustainable design process.

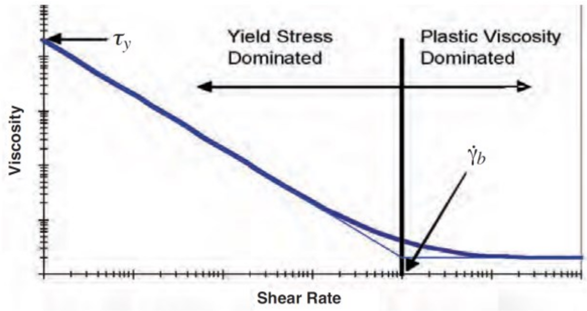

Figure 1. Graphical presentation of Equation 2 showing the boundary shear rate $\dot{\gamma_b}$ (Slatter, 2005)

3. TRANSITIONAL PIPE FLOW

The laminar/turbulent transition is of extreme importance for industrial plant design and operation, because at this point the behaviour of the fluid changes fundamentally. The manner in which an industrial suspension's rheology affects transitional flow behaviour is critically important. For Newtonian fluids, the location of the transition is well established and the calculation is simple. For systems conveying non-Newtonian industrial suspensions, however, this is not the case. Although an accurate method is available (Slatter 1999), 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 (Slatter and Wasp 2000):

$$V_c = 26\sqrt{\frac{\tau_y}{\rho}} \qquad (4)$$

Yield stress domination of the transition behaviour is in fact to be expected, since it has been shown (Slatter 2005) 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.

4. SETTLING IN LAMINAR SHEAR FLOW

Pipelines conveying non-Newtonian industrial suspensions 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 (Cooke 2002). 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 (Pullum et al. 2004), which is usually applied to heterogeneous, settling industrial suspensions, as shown in Figure 2.

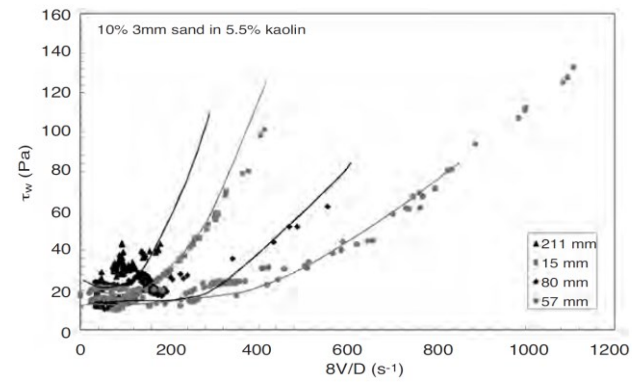

Figure 2. Laminar settling pipe data and two-layer model predictions for sand/clay suspensions in various pipe sizes. (Pullum et al. 2004)

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 industrial suspensions with a yield stress that is high enough to support the largest settleable solid particles (Pullum et al. 2004).

5. 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 industrial processing plants (Slatter et al. 1997). This point is well illustrated by recent texts on the subject (Chhabra and Richardson 1999). 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 (Pienaar et al. 2002). The Research Group has already begun producing such data for practical design purposes (Pienaar et al. 2005).

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 industrial suspensions:

$$H_{Lv} = k_v \frac{V^2}{2g} \qquad (5)$$

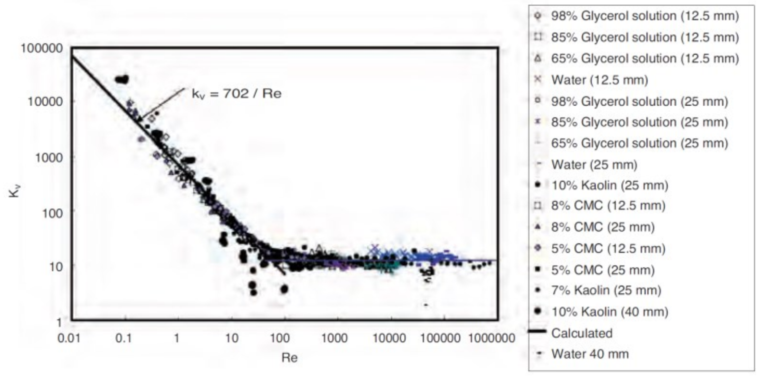

Figure 3. Experimental data from our research group for 12.5mm, 25 mm and 40 mm globe valves (Pienaar et al. 2004)

Figure 3 shows that the work at our research group 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 sustainable design purposes.

6. 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 industrial suspensions handling, these curves must be derated, and the usual approach is to determine the head and efficiency ratios (as industrial suspensions:water performance), referred to as HR and ER respectively. For settling industrial suspensions, standard methods are available, which can usually be used successfully. For non-Newtonian industrial suspensions, there is less certainty, and methods based on the industrial suspensions rheology are presently under investigation. The Walker and Goulas (1984) pump Reynolds number is an effective method to predict pump performance for non-Newtonian industrial suspensions (Sery and Slatter 2002). 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 (2004) present a new analysis, NRep2 based on the pump geometry and the more comprehensive Herschel-Bulkley rheological model. Experimental data from centrifugal pump tests performed at the Research Group have been used to compare these two approaches, as shown in Figure 4.

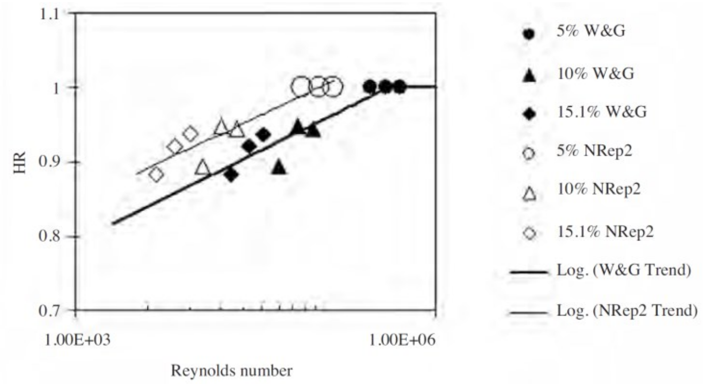

Figure 4. Comparison of the two Reynolds number approaches, using clay slurry experimental data (Sery and Slatter 2004).

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 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 $1x10^6$.

7. LAUNDER FLOW

Launders are used extensively in the industrial processing industry. However, very little is known of the way in which the rheology of the industrial suspensions affects the behaviour of these flows, especially as the industrial suspension becomes more viscous, and laminar flows predominate. Clearly, knowledge of this interaction is vitally important to the understanding of the industrial suspensions environment for plant design. Our approach is to adopt the time-honoured approaches of engineering hydrodynamics, and develop a Reynolds number, which we could use to establish dynamic similarity (Haldenwang et al. 2000). For launder flow, the Fanning friction factor f is given by

$$f = \frac{2\,R_h\,g\sin\theta}{V^2} \tag{6}$$

where R_h is the hydraulic radius and θ is the launder slope. An appropriate Reynolds number (Haldenwang et al. 2000, Haldenwang and Slatter 2006) which accounts for the non-Newtonian viscous stresses in launder flow is

$$Re_{2(YPP)} = \frac{8\rho V^2}{\tau_y + K\left(\frac{2V}{R_h}\right)} \tag{7}$$

Using these as the basis for our approach, laminar flow data can be compared with

$$f = \frac{16}{Re} \tag{8}$$

and turbulent flow data with the Blasius equation

$$f = \frac{0.079}{Re^{0.25}} \tag{9}$$

Using data from the experimental programme at the Research Group, this approach can be evaluated (Haldenwang and Slatter 2006) as presented in Figure 5. Figure 5 shows that this approach has merit, and adequately models the interaction between industrial suspensions 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.

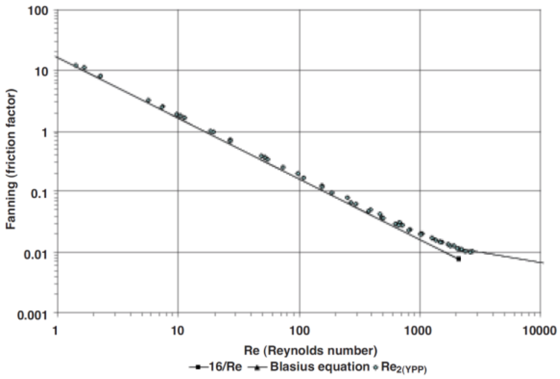

Figure 5. A 6% bentonite slurry flowing in a 300 mm rectangular flume (Haldenwang and Slatter 2006).

8. DISCUSSION

From an industrial processing perspective, the rheological characterisation of the processing suspension is of fundamental importance. Within this context, the measurement and role of the yield stress is of particular prominence. The important role of the boundary shear rate in rheological characterisation has been presented and it has been shown that the yield stress dominates the flow behaviour at stresses and shear rates below the boundary shear rate.

From an industrial suspension process flow perspective, we note the governing role that the yield stress plays in the laminar-turbulent transitional flow behaviour. Since it is a basic assumption that many industrial flow processes operate in the turbulent flow regime, it is important to note the effects that unexpected laminar flows can have on industrial processes.

One of the most basic consequences of unexpected laminar flow, is the shear flow settling of the coarser particles in the suspension. In the absence of turbulent eddies to re-suspend such particles, they will collect on the pipe invert and begin to partially obscure the cross-sectional area of the pipe.

It has also been shown that energy and head losses in valves and fittings become much more significant in laminar flow. This leads to much higher overall head and energy losses than are expected under turbulent flow conditions.

Centrifugal pump performance derating has been presented above, showing that the pump head available for non-viscous materials is significantly reduced in the presence of high viscous stress processing suspensions. This has the potential to reduce operational process flow rates, which can lead to the inability to sustain the industrial flow process conditions mentioned above.

Progress in the flow of non-Newtonian processing suspensions in free surface launder flows has been presented using a Reynolds number approach which includes the full non-Newtonian viscous stress. This approach has shown good agreement with experimental data which is relevant to this industrial context.

Arguably, the most important point to note is that increasing the concentration of the processing suspension can change the flow process behaviour fundamentally. This can lead to turbulent flows becoming laminar, resulting in design and operational problems and pipeline blockages, which can in turn lead to plant shutdowns

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 industrial suspensions rheology. While these statements are often adequate for engineering purposes, the truth is that industrial suspensions rheology depends on physical and chemical state, as well as the flow conditions themselves. There is much research still to be done (Souza Pinto et al. 2014, Souza Pinto et al. 2016, Myers et al. 2017). 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 industrial suspensions environment—a vital precursor for sustainable and sound design.

9. CONCLUSIONS

In this paper we have considered the influence of sustainable industrial practice on process suspension rheology. In particular, we have illustrated the effect of increasing suspension concentration on the flow process rheology. In turn, this results in design and operational challenges in the flow processes commonly encountered in industrial contexts. The impact that process suspension rheology has on transitional pipe flow, particle settling in laminar shear flow, losses in valves and fittings, centrifugal pump de-rating and launder flow have been presented. Our point of departure for this paper has been that sound and sustainable design for industrial suspensions handling rests squarely on an understanding of the industrial suspensions environment. The manner in which industrial suspensions rheology affects flow behaviour in a number of typical plant design hydrodynamic contexts has been presented. Industrial suspensions rheology itself is, however, a complex topic, and research in this area is ongoing

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