The hydraulic transportation of thickened sludges

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Abstract

Industries which pump sludges are under continuous pressure to decrease water content, and increase concentration. Environmentally superior disposal techniques are demanding that such sludges have high mechanical strength properties. This results in a sludge with an increasing viscous character. At high concentration, the viscous forces – which are usually highly non-Newtonian and yield stress in nature – become dominant, and flows inevitably become laminar.

The objective of this paper is to demonstrate the effect and evaluate the impact that increasing non-Newtonian viscous stresses – particularly yield stress – have on the pipelining problem.

An industrially relevant sludge pipe flow study is presented, demonstrating and quantifying the relationship between sludge rheology and flow regime. It is argued that laminar flow will result in settlable solids accumulating on the pipe invert, leading to pipe blockage. Although some practical remedies have been proposed, this problem requires urgent and focussed research.

Keywords: rheology, pipe flow, blockage, laminar, transition, turbulent, yield stress

Notation

Symbol	Description	Unit
D	internal pipe diameter	m
f	Fanning friction factor	
F	constitutive rheological relation function	Pa
He	Hedström number	
K	fluid consistency index, plastic viscosity	Pa.s
r	radius at a point in the pipe	m
R	internal radius of the pipe	m
Re	Reynolds number	
u	point velocity	m/s
V	average velocity	m/s
ρ	fluid density	kg/m^3
τ	shear stress	Pa
τ_y	yield stress	Pa

Subscripts

0	at the pipe wall
c	critical (at the laminar/turbulent transition)

Introduction

Industries which pump sludges are under continuous pressure to decrease water content, and increase concentration. Environmentally superior disposal techniques are demanding that such sludges have high strength mechanical properties. This results in a sludge with an increasing viscous character. At high concentration, the viscous forces – which are usually highly non-Newtonian and yield stress in nature – become dominant, and flows inevitably become laminar (Slatter, 2002).

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Theory and literature

Rheological characterisation

The rheological characterisation of non-Newtonian sludges has received much attention in the literature and the development of this discipline is ongoing. Although more complex rheological models are available, this paper has deliberately targeted a more pragmatic approach, and the simplest model which can accommodate a yield stress has been used. To this end, the Bingham plastic rheological model (Grovier and Aziz, 1972) has been found useful by many researchers to approximate the viscous flow behaviour of non-Newtonian sludges (Xu et al., 1993; Spinosa and Lotita, 2001; Slatter, 2001). The constitutive equation for pipe flow is given by:

$$\tau = \tau_y + K\left[-\frac{du}{dr}\right] \qquad [1]$$

Laminar flow

For laminar pipe flow, the general constitutive rheological relationship F can be cast in the form

$$\tau = F\left(-\frac{du}{dr}\right) \text{ and } -\frac{du}{dr} = F^{-1}(\tau). \qquad [2]$$

Also, for pipe flow, the shear stress $\tau(r)$ varies linearly over the pipe cross-section

$$\tau(r) = \frac{\tau_0}{R} r. \qquad [3]$$

The velocity profile u(r) is obtained by integration of the constitutive rheological relationship, i.e.:

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$$u(r)=\int F^{-1}(\tau(r))dr \quad \text{where } u(R)=0. \qquad [4]$$

The volumetric flow rate Q and bulk velocity V are obtained by integrating the product of annular area elements and the velocity profile over the pipe cross section,

$$Q=\int_0^R u(r)2\pi r\,dr \quad \text{and} \quad V=Q/A. \qquad [5]$$

Applying this procedure to the Bingham plastic case, the constitutive equation can be integrated twice as shown above to produce the velocity profile and the well known Buckingham Equation:-

$$u=\frac{D}{4K\tau_0}\left[\left(\tau_0-\tau_y\right)^2-\left(\tau-\tau_y\right)^2\right], \qquad [6]$$

$$V=\frac{D}{2K\tau_0^3}\left(\tau_0-\tau_y\right)^2\left[\frac{\left(\tau_0-\tau_y\right)^2}{4}+\frac{2\tau_y\left(\tau_0-\tau_y\right)^2}{3}+\frac{\tau_y^2}{2}\right]. \qquad [7]$$

The laminar/turbulent transition

The intersection method first proposed by Hedström is a practical approach which uses the intersection of the laminar and turbulent flow theoretical lines as the laminar/turbulent critical point (Hedström, 1952; Shook and Roco, 1991;Wilson, 1997). This method has given good results as reported by Xu et al., 1993. For industrial design cases with large, industrial size pipes ("large pipe" as defined by Slatter and Wasp (2000), the critical velocity can also be calculated using (ibid)

$$V_{c\,S\,\&\,W}=26\sqrt{\frac{\tau_y}{\rho}}. \qquad [8]$$

Note that critical velocity under these circumstances is independent of pipe diameter.

Turbulent flow

Slatter (1995) developed a turbulent flow model appropriate for non-Newtonian sludges. A roughness Reynolds number for non-Newtonian sludges was formulated to accommodate a particle roughness effect. This formulation can be modified (Slatter and Van Sittert, 1997) to reflect the pipe roughness k as,

$$Re_r=\frac{8\rho V_*^2}{\tau_y+K\left(\frac{8V_*}{k}\right)} \qquad [9]$$

This roughness Reynolds number was used to correlate the classical roughness function B in the same way as for Newtonian fluids. If $Re_r<3.32$ then $B=2.5\ln Re_r+5.5$. This is analogous with smooth wall turbulent flow for which the flow behaviour can be predicted from:

$$\frac{V}{V_*}=2.5\ln\left(\frac{R}{k}\right)+2.5\ln Re_r+1.75 \qquad [10]$$

If $Re_r > 3.32$ then $B = 8.5$. This is analogous with fully developed or rough wall turbulent flow for which the flow behaviour can be predicted from:

$$\frac{V}{V_*}=2.5\ln\left(\frac{R}{k}\right)+4.75 \qquad [11]$$

Analysis and typical applications

Laminar/turbulent transition

For most sewage sludges the density is approximately 1 000 kg/m^3 and the Slatter and Wasp critical velocity equation reduces to:

$$V_{c\,S\,\&\,W}=0.82\sqrt{\tau_y} \qquad [12]$$

This relationship (which is strictly valid for large pipes) is presented in Fig. 1. Since most pipelines will not operate above a velocity of 3 m/s (Slatter and Wasp, 2002), Fig. 1 shows that once the yield stress exceeds approximately 13 Pa, the pipeline will operate in laminar flow.

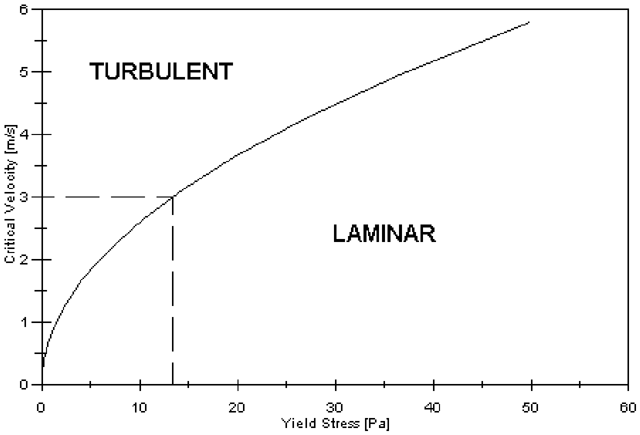

Figure 1
Relationship between critical velocity and yield stress

Pipe flow system curves

In order to apply the above issues to a realistic design case, the sludge characterised by (Slatter, 1997) will be used at 3 concentrations (6%, 8%, and 10%), in a 300mm diameter pipeline. The results of this analysis are presented in Fig. 2.

Figure 2 reinforces the above finding, and shows that turbulence will not be achieved at realistic velocities (i.e. V<3m/s).

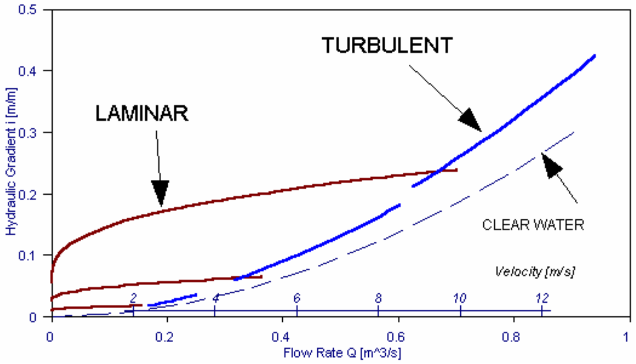

Figure 2
System curve for 6%, 8% and 10% sludge in a 300mm diameter pipeline (from Slatter, 1997)

Discussion

Operating sludge pipelines in laminar flow presents a major problem, as reported by Graham et al. (2002). Since there are no turbulent eddies present, all settleable solids present will report to the pipe invert. In the absence of any similar resuspension mechanism in laminar flow, the settled solids will remain and collect on the pipe invert, inevitably leading to pipeline blockage (15).

One possible remedy is that proposed by Cooke (2002) that the pressure gradient be maintained high enough (1-2 kPa/m) so that the settled bed sliding friction is overcome, and the settled bed will move. However, for long lines this relatively high pressure gradient may not be feasible. Another possibility is to flush the line with a water plug at regular intervals (Gillies et al., 1999), or when elevated line operating pressures are encountered. Provided that there is sufficient operating head reserve, the reduced viscosity of the water will permit turbulent conditions to be established, and the settled solids would then be transported along the pipe.

No conclusive understanding or well researched mechanistic analysis of this phenomenon has yet been established, and laminar flow sludge pipelining remains an urgent unresolved industrial problem, if high concentration sludges are to be hydraulically transported.

Conclusions

It has been shown that high concentration sludge pipelines will operate in the laminar flow regime. This method of operation presents a critical problem – settlable solids will accumulate on the pipe invert and lead to eventual pipe blockage. Although some practical remedies have been proposed, this problem requires urgent and focussed research.

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