Are tube viscometer data valid for suspension flows?

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Abstract

Successful rheological characterization of mineral slurries is fraught with many problems and the need to pump higher concentrations, especially in tailings disposal, has meant that more and more slurries exhibit non-Newtonian behaviour. Capillary tube viscometry is the preferred method of testing and apparently creditable results obtained from stable “homogeneous” suspensions, containing particles with diameters of 10 s and 100 s of microns, are the rule rather than the exception. Settlesable solids suspended in visco-plastic fluids may be stable in the un-sheared condition, but will stratify when the fluid is sheared. This behaviour results in an unobserved stratified flow within the conveying line. For small pipes, such as those used for rheological characterization, the stratified bed flow effect is small and is masked by the viscous nature of the suspending medium. Unfortunately, the stratified bed flow dominates the transport pressure gradients in larger pipes, resulting in often gross under-prediction of full size behaviour. To illustrate this effect, tests conducted with a non-Newtonian carrier fluid in 12 and 25NB (nominal bore) pipes were found to be insensitive to the addition of large (−1 mm) particles at concentrations up to 20% w/w. Conversely, transport characteristics for these suspensions are a strong function of solids concentration in larger pipes, e.g. 100NB. Analysis presented in the paper shows that such behaviour is consistent with the behaviour of high viscosity stratified flows. In practice, tests would not be attempted with such large particles, which make the results obtained even more surprising. The behaviour casts doubts upon the validity of much of the capillary tube data obtained with “normal” slurry size distributions. This phenomenon needs to be understood, if the design of high concentration pumping systems for industrial slurries and pastes is to be performed with any certainty.

Keywords: hydraulic conveying, hydrotransport, stratification, capillary tube, settling, size distribution

1. Introduction

Laminar flow of complex suspensions is now commonplace in mine waste disposal, both above and below ground. Typically the suspensions contain a wide size distribution of solids and exhibit strong non-Newtonian characteristics. These suspensions, often erroneously labelled as pastes, are usually heterogeneous. A coarse solid burden is conveyed as a sliding bed by a non-Newtonian carrier fluid composed of the conveying fluid and finer particles (Pullum and Graham, 2000). The preferred method of rheological analysis for these types of flows is to use a capillary tube viscometer: (i) because the contained solids often preclude the use of rotary viscometry and (ii) because there is a common misconception that capillary tube results are more capable of reproducing the flow behaviour in the larger target pipelines. Since these slurries often appear to be homogeneous, the capillary tube data is often used directly in system design or process control. Clearly the validity of this approach needs to be reviewed.

If the design engineer is fully cognisant of the actual flow behaviour, i.e. that the flow will be stratified requiring a two-layer mechanistic modelling approach (Pullum et al., 2004) such suspensions still pose considerable problems, namely, “what is the largest particle that may be considered to form part of the underlying carrier fluid” and “how are the larger articles removed from the fluid to establish the rheological properties of the carrier fluid?” This latter problem is not trivial, especially for the visco-plastic suspension being considered, and clean separation is especially difficult to achieve in the field.

Elementary consideration of the various inter-particle forces indicate that, depending upon the system, particles in excess of a few microns are too massive to be supported by these forces. Viscous and body forces will dominate their behaviour (Turian et al., 1997; Stickel and Powell, 2005). Consequently, an engineering maximum particle
size of 10–20 µm is often used as the upper limit of these fine particles. Particles larger than 1 mm are clearly too massive to modify the carrier fluid’s rheology, and will form part of the coarse burden (Hanks and Hanks, 1982). However, for systems that form flocs, interaction between these and coarser particles can still occur, implying that perhaps particles larger than 20 µm may still influence the rheology of the carrier fluid (Bhattacharya and Pullum, 1991). This poses a dilemma as it is not clear what constitutes the maximum particle size for the carrier fluid only. A further dilemma is that the inclusion of coarse particles into conventional viscometers will produce errors in measurement and in extreme cases may damage the viscometer itself. A robust method to establish the underlying carrier fluid’s rheology is required, and preferentially one that can include some or all of the coarse burden.

This paper addresses these two interrelated problems.

2. Illustrative example and theory

Fig. 2 shows some results taken during the commissioning trials of the De Beers CTP plant in Kimberly in the Republic of South Africa. (Pullum et al., 2004). The suspension comprised a thickener underflow into which was suspended -2 mm grits at a nominal grits concentration of 10% v/v and the particle size distribution for this suspension is shown in Fig. 1.

The use of a co-disposal suspension is significant as it enabled simple definition of the carrier fluid, i.e. the thickener underflow, and the coarse burden, the grits. The rheology of the thickener underflow was measured using a controlled stress viscometer. For comparison, a mini balanced beam tube viscometer, or BBTV, (Slatter et al., 1998) was loaded with the conveyed suspension of the same carrier plus the -2 mm grits. The BBTV gave essentially the same values as a controlled stress Couette rheometer measuring the thickener underflow alone and both under-predicted the actual pipeline data (350NB). This higher wall shear stress was successfully predicted, however, using a two layer model (Pullum et al., 2004) based on the carrier fluid rheology and grit properties.

The disparity between the results obtained in the small BBTV pipe and the full size pipeline can be explained, once it is recognized that these flows stratify.

In conventional hydraulic conveying, where the fluid is turbulent, it is convenient to define several flow regimes to account for the different suspension behaviours. At high velocities, or with very small particles, the solids are uniformly distributed across the pipe and the flow regime is described as pseudo-homogeneous. At low velocities the solids are confined to a sliding or stationary bed of solids on the bottom of the pipe, in a regime known as stratified. Intermediate flows, where there is a pronounced concentration gradient across the pipe, are known as heterogeneous. By analyzing a large number of data sets using this regime delineation, Newitt’s group (Newitt et al., 1955) concluded that the extra head gradient required to transport solids as a stratified flow would be a simple function of the immersed density alone. They also concluded that it was independent of particle size, and, for industrially sized pipes, the mixture transport head reduced to a simple multiplier of the immersed mixture density, namely 0.8(Sm-1), where Sm is the mixture’s relative density. More recent analyses using stratified or sliding bed models (Wilson, 1976; Gillies et al., 1991; Pullum et al., 2004) also show that the force required to move the bed is essentially independent of pipe size and only a weak function of particle size. Since the solids in a stratified flow are not suspended it is reasonable to assume that similar behaviour will also
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occur under the laminar flow conditions reported here.

A stratified model relies upon a balance between the forces required to move the various layers along the pipe, those resisting this motion and any inter-layer interactions. For a simple two layer model, where all the solids are confined to the lower layer, flow is achieved whenever the pressure gradient across a given pipe section is sufficient to overcome either the resisting forces (wall shear stress x surface areas) in the fluid layer, or those in the bed layer, which are primarily the frictional forces on the underside of the bed. From the above, we expect the bed forces to be essentially constant for industrially sized pipes while the forces associated with moving the fluid through the region above the bed are expected to be a strong function of pipe size. A comparison between the pressure gradient required to move just the non-Newtonian carrier fluid through the region above the bed of solids and that required to move the entire suspension is shown in Fig. 3.

As shown, the forces required to move the fluid through the pipe section above the bed start to dominate at pipe diameters less than 100 mm for this particular system. At diameters less than 50 mm the values required to move the fluid alone or to move the suspensions are virtually indistinguishable.

In the calculations to produce Fig. 3 it was assumed that the entire flow of fluid was over the bed, i.e., the bed was stationary. Close examination of these curves at small pipe sizes shows that they do not collapse onto one curve, but are separated as a function of solids' concentration. This is because the flow of carrier fluid is no longer through a full pipe, but rather through the pipe section above the bed of solids. This passage may be ascribed an equivalent pipe diameter, $D_h$, which, for a fully stratified flow, is a function of the in-situ coarse solids concentration, namely

$$D_h = \frac{D(\pi - \beta \sin \beta \cos \beta)}{\pi - \beta \sin \beta} \quad \text{and} \quad \frac{c_s}{c_v} = \frac{\beta - \sin \beta \cos \beta}{\beta \sin \beta \cos \beta}$$

Where $c_v$ is the in-situ volumetric concentration, $c_s$ is the concentration of the bed, $D$ the pipe diameter and $\beta$ is the bed's half angle defined in Fig. 3.

For moderate solids loadings the variation in pipe diameter is seen to be up to 25%, and the errors in indicated pressure gradient, assuming a stationary bed for the same system, are shown in Fig. 5.

However, for systems such as these, where carrier fluids with yield stresses capable of supporting the mass mean diameter particle are employed, the deposition locus that defines the minimum superficial velocity to ensure bed movement, is very low and often completely suppressed. As the bed velocity approaches the velocity of the fluid above the bed, the equivalent hydraulic diameter approaches the actual pipe diameter, driving the errors shown in Fig. 5 to zero.
For the CTP co-disposal system the deposition locus was very small so that the solids always moved over the velocity range tested. The foregoing analysis provides a plausible explanation of the apparent discrepancy between the suspension properties measured in the BBTV and the pipeline, as shown in Fig. 2.

3. Experimental Results

To test this hypothesis, the small pipe loop at the RMIT University laboratories (Fig. 6) was filled with carboxymethyl cellulose solution (CMC, a power law fluid) and pipeline tests were conducted for the pure carrier fluid and for a 10 and 20% w/w suspension of essentially monosized fine glass beads (1 mm). The pipe loop consists of a 12.7 mm pipe and a 25.4 mm pipe length in series as shown.

A pseudo shear diagram obtained from these tests is shown in Fig. 7 where it can be seen, for the solids' concentration tested, that the addition of the glass has had no significant effect on the pressure results. Thus the clean fluid and suspension data are essentially the same and the moderate change in diameter has also had no effect. However, results for a very similar suspension in a more industrially sized pipe, shows a very marked effect due to coarse solids concentration as shown in Fig. 8.

4. Discussion

The reported behaviour should ring alarm bells for any person dealing with capillary tube data which involve particulate suspensions. While the suspensions reported here contain well-defined coarse particles that are clearly large and would be treated with suspicion if included in any capillary tube data the conjecture is that such behaviour also occurs for much less obviously coarse suspensions when subjected to prolonged shear, e.g. the ~200 µm material cited in Pullum (Pullum et al., 2006). Extreme care should be exercised when using any such data. Normal capillary tube viscometers, often used to analyze such slurries, are incapable of discriminating between the transport gradients required to move the carrier fluid, or the suspension. Consequently, the authors suspect that many predictions of full size pipe behaviour of apparently homogeneous suspensions are underestimated by these techniques. The latter are responsible for the errors incurred, rather than the normal panoply of explanations headed by the favourite “unrepresentative samples” explanation, or that “viscometers cannot be used with suspension flows”.

The reported behaviour can be exploited, however, to extract the underlying carrier fluid rheology from a wide size distribution suspension without the need to answer the question “what is the upper size of my carrier fluid par-
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To do this, it is first necessary to screen out the grossly coarse solids (e.g. >1 mm). Since a small amount of solids will not affect the pressure measurements significantly, the screening requirements for the carrier becomes much less onerous and only as much of the coarse particles, as is practical, are removed. The resulting suspension is then pumped through a small diameter pipe with a diameter at least ten times the maximum solids diameter, but substantially smaller than the actual pipeline (e.g. < 30 mm). The resulting flow curves are then analyzed using normal capillary tube methods. In keeping with standard tube viscometry practice, it should be noted that tests need to be conducted in at least two different diameter pipes. This will enable detection and correction for viscometric artefacts such as wall slip.

Following such a procedure, it is unlikely that any more than a 5% concentration of coarse solids would be used (i.e. c, -0.05), even if the carrier fluid had a very high yield stress. Without any quantitative knowledge of the coarse solids concentration, and with reference to Fig. 5, it is clear that the maximum error in measuring the carrier fluid rheology would be of order 15%. However, this bounding error assumes that the solids do not move within the pipe, implying a very low yield stress (or zero shear viscosity). Such materials are very easy to screen and it would be expected that the screening would produce a suspension with a much lower coarse solids content. Either this reduction in solids, or the fact that the solids were moving, would reduce the error substantially to that shown typically in Fig. 7. The resulting moderate error is comparable to errors concerned with the other parameters used to model the entire suspension, and so is acceptable.

Since the seminal work of (Metzner and Reed, 1955), it has become part of the paradigm of pipeline design for laminar homogenous non-Newtonian fluids, that scale-up from collinear laminar flow pipe curves is trivial. Arguably, the most important point of our present work is that collinear laminar flow pipe curves in small pipes do not automatically imply homogeneous behaviour. The need to independently detect and identify laminar flow settling behaviour is critically important, and subsequent scale-up must be performed using a suitable mechanistic two-layer model. The test approach advocated in this paper applies to the carrier fluid only, and cannot be used for scale up without such a mechanistic approach and the additional data for the coarse solids fraction.

5. Conclusions

A flag has been raised to warn users of possible instrument artefacts associated with capillary tube measurements in suspension rheology. In particular the capillary tube measurements do not allow for the detection of stratification of the coarse solids in laminar flow which has a significant impact on full scale pipeline pressure gradients.

A method has been presented that allows the underlying carrier fluid rheology of a wide size distribution suspension to be obtained, with an accuracy sufficient for modelling the entire suspension, when used in conjunction with a suitable stratified model and coarse particles properties. The method does not require that the user estimate the size of solids that comprise the carrier fluid, or require that all of these “coarse” solids be scrupulously removed from the suspension before testing, thus providing a simple robust method that is ideally suited for the field as well as the laboratory.

Nomenclature

- $c_b$: Bed volumetric concentration.
- $c_v$: In-situ volumetric concentration.
- $D$: Pipe diameter, m.
- $D_h$: Hydraulic diameter, m.
- $k$: Fluid consistency index, Pa·s.
- $L$: Length, m.
- $n$: Flow behaviour index.
- $Q$: Flow rate, m³/s.
- $S_r$: Mixture relative density.
- $V$: Bulk velocity, m/s.
- $\beta$: Bed half angle, radians.
- $\rho_f$: Fluid’s density, kg/m³.
- $\rho_s$: Solid’s density, kg/m³.
- $\tau_y$: Yield stress, Pa.
- $\tau_w$: Wall shear stress, Pa.

References


Pullum, L., L. J. W. Graham and P. T. Slatter, 2004, A non-Newtonian two layer model and its application to high density hydrotransport. 16th International Conference on Hydrotrans-
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